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This Month—*Summer Convention Issue*

Front Cover

Where the James River breaks through the Blue Ridge Mountains near Glasgow, Va., as seen from the Lynchburg-Natural Bridge highway (U.S. No. 60). This is but one of the many beauty spots that may be enjoyed by those motoring to the Institute's 50th annual summer convention. The hydroelectric station at the left is the 2,400-kva Balcony Falls plant of the Virginia Public Service Company

Photo by F. A. Lewis (A'31)

Educational Series—No. 6

A.I.E.E. Papers

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To each member of the A.I.E.E.

Dear Sir:

Under date of November 8, 1933, we wrote you asking for your support of the membership activities of the Institute. We asked you specifically to send in the name of one person who you feel should be asked to join the Institute. Now we are asking you to do this again. Just send the name to the chairman of the membership committee of your Section. Please do this now.

Since we wrote you last, 345 applications have been submitted for membership from other than students. Your contribution helped to make this possible. We are asking for your continued support.

Very truly yours,

Chairman National Membership Committee

Structure of Atoms and Molecules

Electronic Theory of Valence

By MAURICE L. HUGGINS The Johns Hopkins Univ.,
FELLOW AM. PHYS. SOC. Baltimore, Md.

A digest of present theories regarding the structure of atoms and molecules is presented herewith. In an article of this length it is impossible to show adequately how bulk properties of substances are related to atomic properties; the article is intended primarily as a general introduction to the subject, and for those wishing to delve deeper into the matter a list of references is given at the end of the article. This is the sixth of a series of special articles prepared under sponsorship of the A.I.E.E. committee on education.

THE POSTULATE that matter is composed of tiny discrete *atoms* dates back to the early Greeks. Dalton in 1808, however, was the first to show how such an assumption explains the constancy of composition of pure substances and the simple relationships existing between the compositions of different substances composed of the same *elements*, for instance carbon monoxide, CO, and carbon dioxide, CO_2.

Dalton assumed that *compounds* consist of "compound atoms," now called *molecules*, but there was no satisfactory way of determining the correct molecular formulas (*e. g.*, HO or H_2O or HO_2 for water) until Avogadro in 1811 showed that the densities of different gases under identical conditions of temperature and pressure are proportional to the weights of the molecules of which they are composed. Knowing the formulas, relative *atomic weights* then could be calculated from measurements of the weights of substances consumed and formed in chemical reactions. The names, symbols, and atomic weights of many of the elements are listed in Table I.

Nothing was known regarding the structures of atoms until the discovery (Thomson, 1895) that they contain negatively charged *electrons*. Later, evidence was presented (Rutherford, 1911) to show that these are in continuous rotation around a minute positively charged *nucleus*. All electrons in all atoms now are known to be alike in having the same charge ($-e$) and the same mass. The mass of the lightest nucleus, that of hydrogen, is about 1,840 times that of an electron. For most purposes, therefore, the mass of an atomic nucleus can be considered to be the same as the mass or weight of the whole atom. The charge on the nucleus is always positive and equal to an integer N (called the *atomic number*) times e, the magnitude of the electron charge. The value of N is 1 for hydrogen, 2 for helium, 3 for lithium, etc., increasing in the same order as the atomic weight (with 3 exceptions) as an examination of Table I will show.

The nucleus of a hydrogen atom consists of a single *proton*, a particle with a charge of $+e$ and a mass of approximately one atomic weight unit. The nucleuses of other elements are complex, containing protons, *neutrons* (Bothe and Becker, 1930), electrons, and *positrons* (Anderson, 1932). A neutron is an uncharged particle of (practically at least) the same mass as a proton. A positron has (approximately at least) the same magnitude of charge and mass as an electron; its charge, however, is of opposite sign. Although the masses and the net charges of most kinds of nucleuses are known, the arrangements and relative motions of the component particles and in most cases even the numbers of each component at present are unknown.

The charge on the nucleus of an atom determines the number of electrons rotating around it and so the chemical and physical properties, other than those that depend on the mass. In many instances nucleuses that differ in mass, because of differences in the numbers of protons and neutrons they contain, have the same charge and hence are of the same element. Atoms containing these nucleuses of differing mass are called *isotopes* (Soddy and Fajans, 1913). The most important example is that of hydrogen. Although most atoms of hydrogen have nucleuses consisting of a single proton, as stated previously, it has been shown recently (Urey, Brickwedde, and Murphy, 1932) that about 1 atom in 5,000 has a mass twice as great as that of a proton. The "heavy hydrogen" or "deuterium" nucleus consists of one proton and one neutron. Molecules containing heavy hydrogen atoms differ very slightly in chemical and physical properties from corresponding molecules containing ordinary hydrogen atoms. Differences between the properties of isotopes of any other element (and between corresponding compounds containing these isotopes) are so extremely small as to make their separation very difficult.

The elements can be listed in the order of their atomic numbers in such a way (Table I) that elements with similar properties are placed in the same vertical column (Mendeleëff, 1869). For example, helium, neon, argon, and krypton are similar in being inert gases, forming no stable chemical compounds whatever. Fluorine, chlorine, bromine, and iodine are colored substances consisting of diatomic molecules, F_2, Cl_2, etc. Melting and boiling points increase regularly in the series. They react vigorously with many other elements, forming compounds with similar formulas—HF, HCl, HBr, HI; NaF,

Table I—An Abbreviated Periodic Table

	1 H 1.0 Hydrogen *1*						
2 He 4.0 Helium 2	3 Li 6.9 Lithium 2, *1*	4 Be 9.0 Beryllium 2, *2*	5 B 10.8 Boron 2, *3*	6 C 12.0 Carbon 2, *4*	7 N 14.0 Nitrogen 2, *5*	8 O 16.0 Oxygen 2, *6*	9 F 19.0 Fluorine 2, *7*
10 Ne 20.2 Neon 2, 8	11 Na 23.0 Sodium 2, 8, *1*	12 Mg 24.3 Magnesium 2, 8, *2*	13 Al 27.0 Aluminum 2, 8, *3*	14 Si 28.1 Silicon 2, 8, *4*	15 P 31.0 Phosphorus 2, 8, *5*	16 S 32.1 Sulfur 2, 8, *6*	17 Cl 35.5 Chlorine 2, 8, *7*
18 A 39.9 Argon 2, 8, 8	19 K 39.1 Potassium 2, 8, 8, *1*	20 Ca 40.1 Calcium 2, 8, 8, *2*					
	29 Cu 63.6 Copper 2, 8, 18, *1*	30 Zn 65.4 Zinc 2, 8, 18, *2*	31 Ga 69.7 Gallium 2, 8, 18, *3*	32 Ge 72.6 Germanium 2, 8, 18, *4*	33 As 74.9 Arsenic 2, 8, 18, *5*	34 Se 79.2 Selenium 2, 8, 18, *6*	35 Br 79.9 Bromine 2, 8, 18, *7*
36 Kr 83.7 Krypton 2, 8, 18, 8	37 Rb 85.4 Rubidium 2, 8, 18, 8, *1*	38 Sr 87.6 Strontium 2, 8, 18, 8, *2*					
	47 Ag 107.9 Silver 2, 8, 18, 18, *1*	48 Cd 112.4 Cadmium 2, 8, 18, 18, *2*	49 In 114.8 Indium 2, 8, 18, 18, *3*	50 Sn 118.7 Tin 2, 8, 18, 18, *4*	51 Sb 121.8 Antimony 2, 8, 18, 18, *5*	52 Te 127.5 Tellurium 2, 8, 18, 18, *6*	53 I 126.9 Iodine 2, 8, 18, 18, *7*

To the left of each symbol (F) is the atomic number (9); to the right is the atomic weight (19.0). Below the name (Fluorine) is the distribution of extranuclear electrons into shells (2, 7) in order from the nucleus out. The numeral in *italics* indicates the number of valence electrons in an uncharged atom.

NaCl . . . . .; MgF_2, $MgCl_2$ . . . . .; etc. Each of the other columns of Table I likewise contains a group of elements similar to each other.

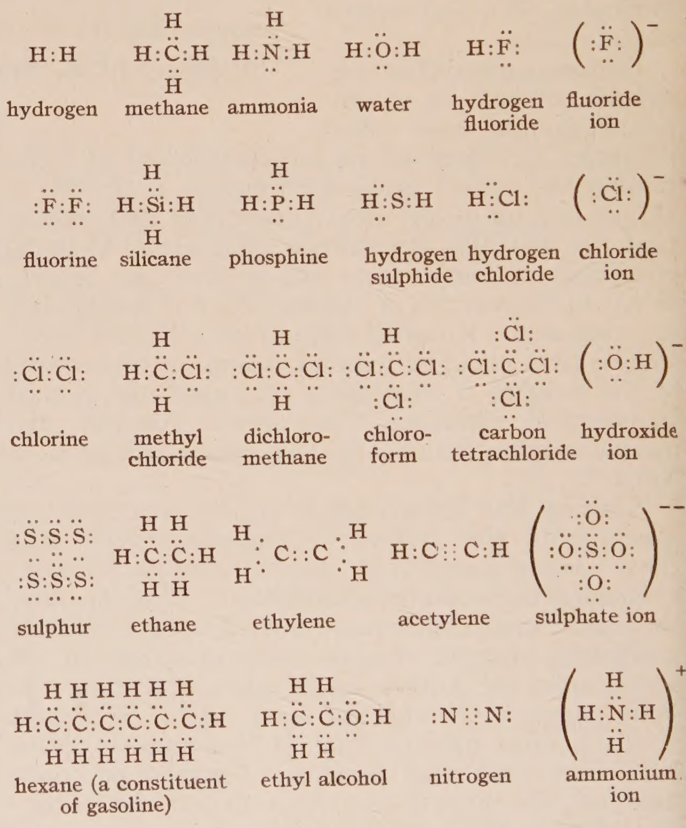
Lewis (1902) and Thomson (1904) showed that the periodicity in properties exhibited by the elements can be accounted for by assuming that the electrons (outside of the nucleus) are in shells, the number of electrons in the outermost shell of an uncharged atom determining the column of the periodic table in which the element belongs. The distribution into shells is indicated for each element in Table I.

The word *kernel* frequently is used to signify all of the atom but the valence shell. The charge on the kernel is positive or zero and equal in magnitude to the number of valence electrons in the uncharged atom times *e*, the charge on each electron.

Uncharged atoms can either lose electrons or gain them, becoming positively or negatively charged atoms or *ions:* H^+, Na^+, Mg^{++}, F^-, Cl^-, etc. Thomson assumed all chemical combination to be the result of electron transfers from atom to atom, the oppositely charged ions so produced attracting each other. Lewis (1916) showed that electrons are also *shared*, usually in pairs. Including shared electrons and those transferred from other atoms, *atoms having kernel charges of +4e or greater nearly always have 8-electron valence shells* in stable compounds or in the uncombined elements at ordinary temperatures. In molecules containing atoms with kernel charges less than 4*e*, each of these atoms usually shares with other atoms a number of electron pairs equal to the kernel charge. Although 2 adjacent atoms in a molecule normally share but one electron pair between them, an atom of carbon, nitrogen, and oxygen can form *double* and *triple bonds*, consisting of 2 and 3 shared electron pairs, with another atom of one of these elements.

In any neutral molecule the total number of valence electrons, of course, must equal the sum of the charges on the kernels. In an ion the difference between these quantities gives the ionic charge.

To illustrate the statements in the 2 preceding paragraphs, *dot formulas* of some simple molecules and ions are presented herewith. In these the kernels are represented by the atomic symbols, the valence electrons by dots.



The shared electrons in the H_2, F_2, Cl_2, N_2, and S_8 molecules and those shared between carbon atoms in C_2H_6, C_2H_4, C_2H_8 are shared equally by the 2 atoms. These bonds are said to be *nonpolar*. Bonds between unlike atoms are at least slightly *polar*, the shared electrons, in general, being more tightly held by one of the 2 bonded atoms than by the other. The one holding the electrons more tightly—in whose vicinity each of the 2 electrons spends more than half of its time—is said to be the more negative.

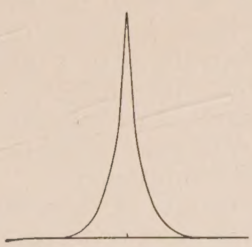
Using a simple but partially incorrect theory—

involving the assumption that the electrons rotate continuously around the nucleus of an atom, but only in certain particular circular or elliptical orbits—Bohr (1913) was able to calculate the different possible energy states of atoms corresponding to these orbits and from them the frequencies of light emitted and absorbed by these atoms. More recently it has been shown that the same quantitative agreement can be obtained (with better concordance with experiment in a few instances in which the Bohr theory led to unsatisfactory results) assuming a more random type of electron motion. A *new quantum mechanics*, of which the ordinary mechanics is a special case, has been developed (deBroglie, 1922; Heisenberg, 1925; Schrödinger, 1926). With this it is possible to calculate what atomic energy states are possible and, for each of these, the probability of an electron being in any given position relative to the nucleus. An *electron probability* distribution so obtained also can be considered as a time-average *electron density* distribution. These distributions, for a hydrogen atom in 3 different energy states, are represented somewhat qualitatively in Fig. 1.

The electron-pair bond of Lewis has been shown (Heitler and London, 1927) to consist of 2 electrons rotating about 2 nucleuses, each of these electrons having a probability distribution concentrated near the line joining the nucleuses (Fig. 2). Each electron spins on its own axis while it rotates about the nucleuses, but the 2 spins are in opposite directions. With some exceptions the unshared electrons in atoms under ordinary conditions are paired similarly.

Since its introduction, the new quantum mechanics treatment of molecules has been extended by Pauling (1931) Slater (1931) and others to much more complicated cases. Among other things it has been shown that a shell of 4 pairs of electrons, with their probability distributions having maxima directed toward the corners of a tetrahedron, is especially stable and that the strength of a bond between 2 atoms is roughly proportional to the amount of overlapping of the probability distributions for the single atoms. Thus the observed orientations of the bonds (i. e., the atomic centerlines) in H_2O, NH_3, CH_4, and many other compounds approximately toward 2, 3, or 4 corners of a tetrahedron are accounted for.

Quantum mechanics, moreover, accounts for the exceptions to the usual tetrahedral arrangement. Some atoms form bonds with 4 others situated at the corners of a square; in other cases 6 bonds connect an atom to other atoms located at the corners of an imaginary octahedron or trigonal prism. The new mechanics shows under what circumstances such arrangements have greater stability than a tetrahedral one.



Figs. 1a (above) and 1b (below). Variation of electron probability (average electron density) with distance from the nucleus for 2 energy states of the hydrogen atom

These probability distributions are spherically symmetrical; the scales are arbitrary

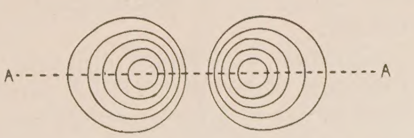


Fig. 1c. Representation by contours of a cross section of the electron probability distribution for a third energy state of the hydrogen atom (qualitative only)

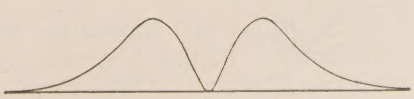


Fig. 1d. Electron probability along a line AA of Fig. 1c

Structures of Crystals

Much of the present knowledge of molecular structures and of the forces between atoms has come from studies of the structures of crystals. Many years ago crystallographers had shown that to account for the forms and other crystallographic properties of crystals it was necessary to assume that they consist of regular arrangements of discrete particles—atoms or molecules—with distances between their centers of the order of magnitude of 10^{-8} cm. These distances are about the same as the wave lengths of X rays, which are otherwise like visible light. Noting this correspondence, Laue, Friedrich, and Knipping (1912) sent a beam of X rays through a thin crystal and recorded the diffraction effects on a photographic plate. The crystal acts as a 3-dimensional diffraction grating. The following year W. H. and W. L. Bragg showed how to use X ray diffractions from crystals to deduce the crystal structures. Since then a great many structures have been analyzed by this means.

Some important relationships between crystal structures and the structures of the component atoms are well illustrated by a consideration of the crystal structures of some uncombined elements. As already pointed out, a 7-valence-electron atom (F, Cl, Br, I) forms diatomic molecules. These

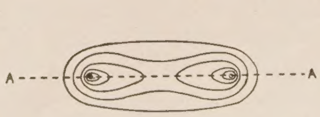


Fig. 2a. Representation by contours of a cross section of the electron probability distribution in a hydrogen molecule (qualitative only)

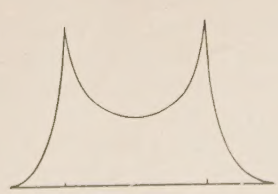


Fig. 2b. Electron probability along a line AA (Fig. 2a) through the atomic centers in a hydrogen molecule

molecules exist as distinct units even in the solid state. In solid iodine, for instance, the distance between the centers of closest atoms in the same molecule is about 2.7×10^{-8} cm; that between closest atomic centers in different molecules is about 3.6×10^{-8} cm. Intermolecular attractions are quite weak; hence, the substance is easily liquefied and vaporized.

An uncharged sulphur atom has 6 valence electrons. The 2 common crystalline forms of this element are aggregates of molecules, each molecule containing 8 sulphur atoms. The dot formula for this molecule already has been given.

Selenium, also with 6 valence electrons, similarly forms Se_8 molecules. In addition, a form is known in which the atoms are bonded together in parallel spiral strings, extending completely through the crystal:

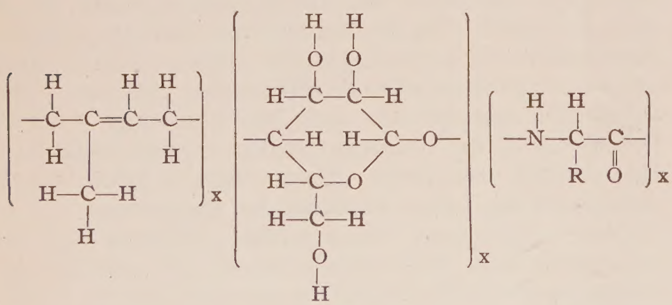
```
 ..  ..  ..  ..  ..
:Se:Se:Se:Se:Se
 ..  ..  ..  ..  ..

 ..  ..  ..  ..  ..
:Se:Se:Se:Se:Se
 ..  ..  ..  ..  ..

 ..  ..  ..  ..  ..
:Se:Se:Se:Se:Se
 ..  ..  ..  ..  ..
```

Cleavage across these strings is difficult; between the strings it is very easy. This crystal form has much higher melting and sublimation points than the form containing ring molecules. Moreover, it dissolves only when acted upon by substances capable of breaking the Se:Se bonds, whereas the ring molecules dissolve readily in suitable solvents.

It may be mentioned that other giant *string molecules* occur in rubber, cellulose, proteins, and many other substances. Representing each shared electron-pair bond by a straight line, the formulas of these are:



rubber cellulose protein

In the formula for protein, "R" denotes any one of many groups of atoms—CH_3, C_2H_5, and more complicated ones.

An uncharged atom of phosphorus or arsenic has 5 valence electrons; 3 additional electrons are required for a complete valence shell. In the absence of atoms of other kinds, therefore, it forms 3 electron-pair bonds with other like atoms. This accounts both for the tetrahedral P_4 and As_4 molecules (Fig. 3) and for the giant *layer molecules* existing in one solid form of the latter element and probably also in one form of the other (Fig. 4).

Many compounds also form layer molecules. An example is mercuric iodide, HgI_2. A portion of a layer of this substance can be represented by the dot formula:

```
   ..     ..     ..
 Hg:I:Hg:I:Hg:I:
 ..  ..  ..  ..  ..
:I:   :I:   :I:
 ..  ..  ..  ..  ..
 Hg:I:Hg:I:Hg:I:
 ..  ..  ..  ..  ..
:I:   :I:   :I:
 ..  ..  ..  ..  ..
 Hg:I:Hg:I:Hg:I:
 ..  ..  ..  ..  ..
:I:   :I:   :I:
 ..    ..    ..
```

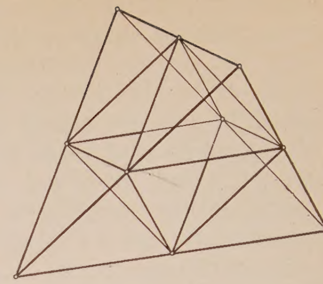
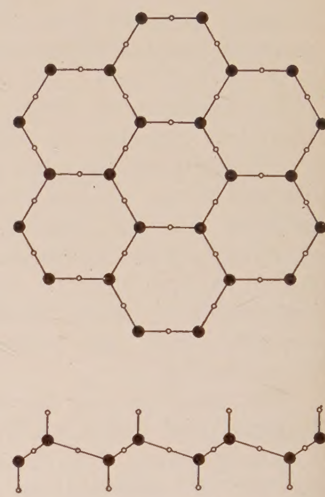


Fig. 3. A representation of the P_4 or As_4 molecule

Each atom is depicted as a regular tetrahedron, the small circles at the tetrahedron corners representing pairs of valence electrons



The large dots are the atomic kernels; the small circles, pairs of valence electrons. As in the As_4 molecule (Fig. 3) there are 4 valence electron pairs around each kernel, 3 of these being shared with other atoms

Fig. 4. Diagram representing a portion of a layer molecule of arsenic, in plan and elevation

Carbon, silicon, and other 4-electron elements form crystals in which the whole structure constitutes a single giant molecule (Fig. 5). Each atom shares electron pairs with 4 other like atoms. Silicon carbide, SiC, zinc sulphide, ZnS, cuprous chloride, CuCl, and many other substances with the same average number of valence electrons per atom have the same type of arrangement.

In crystals of elements having less than 4 electrons per atom no structure is possible in which each atom has a complete valence shell. The atomic centers are usually in a "close-packed" arrangement, each having 12 neighbors, as in an assemblage of spheres packed together as closely as possible. Although the valence electrons in most cases do not form electron-pair bonds between the atoms, they are not tightly held and are easily transferred from one atom to a neighboring one. These are the metals.

Crystals of sodium chloride, NaCl (Fig. 6), ammonium chloride, NH_4Cl, and many other compounds are regular assemblages of positive and negative ions. Each ion is surrounded, usually symmetrically, by several others of opposite charge.

Structures in Liquids, Glasses, and Solutions

In a liquid the molecules are in a random and constantly changing arrangement. In some instances, however, they form small aggregates of

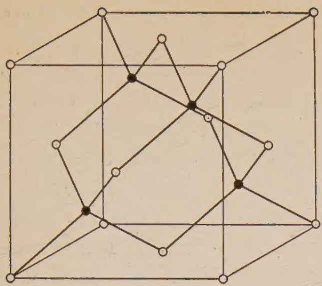


Fig. 5. A portion of the diamond structure

Both dots and circles represent carbon atoms. Each is bonded tetrahedrally by electron-pair bonds to 4 others. The same type of arrangement, but with 2 kinds of atoms, is possessed by SiC, CuCl, ZnS, and other compounds

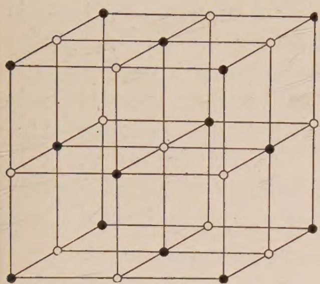


Fig. 6. A portion of the sodium chloride (NaCl) structure

Dots denote the centers of Na^+ (or Cl^-)ions; circles, the centers of Cl^- (or Na^+) ions. Many other ionic crystals have this type of arrangement

regular or semiregular structure. Liquid hexane, C_6H_{14} (see the dot formula given previously) contains groups of zigzag molecules having their chain axes approximately parallel to each other. In a liquid consisting of polar molecules, such as water, the positive ends (hydrogens) of each molecule tend to point toward the negative (oxygen) ends of other molecules. This gives a semiregular though constantly changing structure to the whole body of liquid. Sodium chloride is ionized in the liquid state as in the solid. The instantaneous arrangement in the liquid possesses some degree of regularity; this is a result of the tendency of each positive ion, Na^+, to have as immediate neighbors only negative ions, Cl^-, and the similar tendency of each negative ion to be surrounded by a shell of positive ions.

A *glass* lacks the regularity of arrangement of a crystal and the mobility of a liquid. Each atom vibrates about a fixed position, being restrained by the surrounding atoms. As in the case of liquid sodium chloride, each of the more positive atoms or ions (sodium, calcium, and silicon in ordinary glass) tends to be surrounded by more negative atoms or ions (oxygen) and *vice versa*.

In a water solution of an ionizing substance such as sodium chloride, each ion is *hydrated;* that is, it attracts and carries with it a shell of water molecules. The negative (oxygen) ends of these are closer to the central ion if it is positively charged; the positive (hydrogen) ends are closer if the ion has a negative charge. Occasionally, especially in concentrated solution, a water molecule in the shell surrounding a positive ion is replaced by a negative ion; likewise a positive ion occasionally enters the shell surrounding a negative ion.

Water solutions of polar but un-ionized molecules also are hydrated to some extent, the polar ends of these molecules attracting the ends of the water molecules having opposite polarity. In solvents which, unlike water, consist of molecules having little or no polarity, there is little solvation.

Some Properties of Atoms and Interatomic Bonds

Many physical and chemical properties of substances are closely related to the tightness with which the valence electrons of the component atoms are held. This may be measured by the *ionization energy,* the energy increase in the process of removing one electron completely from the atom:

$$M \longrightarrow M^+ + E^-$$

The ionization energies of some of the elements are given in Table II. These are in kilocalories per *gram atom.* One gram atom contains 0.6064×10^{24} atoms; it has a mass in grams equal to the atomic weight (1.008 g of H, 4.002 g of He, 16.000 g of O, etc.). To remove a second electron from an atom always requires more energy than to remove the first.

With some exceptions, for atoms with similar kernels (those in the same *row* of Table II) the greater the kernel charge the greater the energy required to remove a valence electron. Again with some exceptions, for atoms having the same kernel charge (those in the same *column* of Table II) the larger the atomic number the smaller the ionization energy. Elements with the smaller values of ionization energy are metals; those with the larger values are nonmetals.

Those elements having the greatest ionization energies have an attraction for an additional electron. The energy decrease in the change is called

$$X + E^- \longrightarrow X^-$$

the *electron affinity.* The electron affinities of F, Cl, Br, and I are about 98, 88, 83, and 76 kilocalories per gram atom, respectively.

It is evident from a consideration of the electron probability distribution in atoms that the "size" of an atom has no absolute meaning; however, *relative* sizes with a definite meaning can be determined. It is useful to define an *atomic radius* as "that distance which, when added to the corresponding 'radius' of another atom gives the equilibrium distance between the 2 in a molecule or crystal"; that is:

$$2\,r_c = d_{C-C} \qquad \text{and} \qquad r_C + r_H = d_{C-H}$$

Distances between atoms in a large number of molecules and crystals are known. It is found, however, that in general atomic radii are not additive. No set of radii can be obtained that will lead to the observed interatomic distances in substances of widely differing types.

An approach to additivity of radii is obtained if different sets of radii are used for different types of attractive forces between the atoms—one set for ionic compounds, another for atoms joined by electron-pair bonds, and a third for metals. Still greater additivity results if, for each of these classes, different sets of radii are used for different *coördination numbers.* The coördination number is merely the number of close neighbors. Some of the more useful and more accurately known radii are given in Table II.

As a rough rule, ionic radii for a coördination number (co. No.) of 8 are about 3 per cent greater

than those for a coördination number of 6. Similarly, octahedral atomic radii (co. No., 6) are about 5 per cent greater than the corresponding tetrahedral radii (co. No., 4). "Metallic" radii for a coördination number of 8 are about 3 per cent smaller than those for a coördination number of 12. In most cases, adding the proper radii together gives the corresponding interatomic distance correct to within 0.02×10^{-8} cm.

Table III gives relative values of the *negativity* of some atoms, for use in determining the direction and approximate magnitude of the polarity of different bonds. A bond between carbon (negativity, 2.6 units) and chlorine (negativity, 4.5 units) has a polarity of 1.9 units, the chlorine end of the bond being the more negative. Bond polarities are important in determining attractions between different molecules (hence melting and boiling points) and mechanisms of chemical reactions. A highly polar bond is more readily split "unsymmetrically" (both electrons of the shared pair remaining with the more negative atom) than "symmetrically" (one electron staying with each atom).

The strength of a bond may be measured by its *bond energy*, the energy that must be added to break the bond so that one of the shared electrons goes with each atom. Bond energy values are approximately additive if the bonds have little polarity. Since the N:N and Cl:Cl bonds have no polarity and the polarity of an N:Cl bond is very small, the bond energies of these bonds are about 34, 56, and 45 kilocalories, respectively, calculated from the nonpolar atomic bond energies given in Table III.

For more polar bonds the bond energy can be calculated quite roughly by adding to the *nonpolar bond energy*, obtained on the assumption of additivity, the *polarity energy*. This latter quantity is obtained by squaring the difference between the negativities (Pauling, 1932). If, for instance, it is desired to calculate the bond energy of a C:O bond:

Nonpolar bond energy $= 42 + 17 = 59$ kilocalories
Polarity energy $= (6.7 - 2.6)^2 = 17$ kilocalories

Total bond energy of C:O bond $= 76$ kilocalories

In an article of this length it is impossible to show adequately how the bulk properties of substances are related to atomic properties and to the arrangements of atoms. Such correlations, however, can be made and often are very enlightening. The more that is known about atomic structures and the forces between atoms, the more can be predicted about the structures, interatomic distances, forces, and energy relationships in aggregates of atoms and from these about the gross physical and chemical properties of different kinds of matter. A better understanding of these things is of use in many widely different fields of science and industry.

Table II—Ionization Energies and Ionic and Atomic Radii

		H						
		312						
	He	Li	Be	B	C	N	O	F
	564	*124*	*214*	*191*	*259*	*334*	*312*	*429*
(a)		0.60	0.31				1.40	1.36
(b)		1.35	1.07	0.89	0.77	0.70	0.66	0.64
(c)			1.11					
	Ne	Na	Mg	Al	Si	P	S	Cl
	495	*118*	*175*	*137*	*187*	*256*	*238*	*299*
(a)		0.95	0.65				1.84	1.81
(b)		1.70	1.40	1.26	1.17	1.10	1.04	0.99
(c)			1.59	1.43				
	A	K	Ca					
	361	*100*	*140*					
(a)		1.33	0.99					
(b)								
(c)			1.96					
		Cu	Zn	Ga	Ge	As	Se	Br
		177	*216*	*138*	*186*	*230*	*219*	*272*
(a)		0.96	0.74				1.98	1.95
(b)		1.35	1.31	1.26	1.22	1.18	1.14	1.11
(c)		1.28	1.37		1.39			
	Kr	Rb	Sr					
	322	*96*	*131*					
(a)		1.48	1.13					
(b)								
(c)			2.15					
		Ag	Cd	In	Sn	Sb	Te	I
		174	*206*	*133*	*168*	*192*	*206*	*241*
(a)		1.26	0.97				2.21	2.16
(b)		1.53	1.48	1.44	1.40	1.36	1.32	1.28
(c)		1.44	1.52	1.57	1.58	1.61		

Ionization energies in kilocalories per gram atom are shown in *italic* type.
(a) = Ionic radius (in 10^{-8} cm) for a coördination number of 6.
(b) = Tetrahedral atomic radius (in 10^{-8} cm) for a coördination number of 4.
(c) = "Metallic" radius (in 10^{-8} cm) for a coördination number of 12.

Table III—Nonpolar Atomic Bond Energies (*italic* numerals) and Negativities

H	C	N	O	F	
51	*42*	*17*	*17*	*32*	kilocalories per gram atom
0	2.6	4.6	6.7	9.6	polarity units
	Si	P	S	Cl	
	?	*?*	*32*	*28*	
	−0.7	0.5	2.1	4.5	
		As	Se	Br	
		44	*12*	*22*	
		0	0	3.6	
		Sb	Te	I	
		35 ?	*17*	*17*	
		0	0	1.9	

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Engineers of the Next Generation

As the social and economic significance of engineering becomes plainer every day, the world looks to the engineer of the future as a leader capable of shouldering broader social responsibilities. The organization of the Engineers Council for Professional Development is the first step in preparing the coming generation of engineers for the tasks ahead. This paper describes the formation, aims, and activities of E.C.P.D. and espouses its importance.

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THE engineering profession of today is charged with the education and other preparation of the next generation of engineers. If it does not address itself to this task and with a full realization of its own shortcomings, this next generation will find itself as handicapped as the profession is now. In the Engineers' Council for Professional Development an organization capable of taking the first steps in the desired direction has been created, and it contains the potential power to develop a united engineering profession that knows where it is headed and how to get there. Not that huge affairs can be planned in advance and completely controlled in progress (as is now so commonly believed, possibly in desperation); but, that affairs which are of such small magnitude and are influenced by so few factors that they can be encompassed completely or nearly so by human mentality, are much more likely to maintain an ordered and intelligent course if properly planned in advance and properly supervised later.

A large part of the proposed activities of E.C.P.D. has to do with engineering education in the broadest interpretation of that term. It contemplates a conscious planning and a conscious following of the education of individuals to the end that they may be able best to fill their places in the world. In fact, all else thus far contemplated is nothing more than the setting up of yardsticks to determine the acquisition of such education and the formulation of names and definitions.

The E.C.P.D. is not the end and all, nor is its organization perfect or its program complete and flawless; but it possesses the required potentialities for achieving its aims and it is capable of functioning advantageously now, while we are engaged in learning from experience where and how it and its program should be changed. The organization of the E.C.P.D. came about largely as a result of recognition on the part of the profession of the following facts:

1. More than half the states in this country have laws for licensing engineers, requiring the establishment and maintenance of state boards to perform the function of licensing, and it is very probable that the other states will enact similar laws shortly.

2. To be effective these licensing laws must define in some way both the education and other training and the degree of accomplishment required of a candidate for license.

3. Laws already in existence indicate that state licensing boards will adopt lists of accredited engineering schools. In other words, these bodies, which are likely to be more or less political in character in at least some states, will be authorized by law to determine which engineering schools of the nation meet acceptable standards in their respective states.

4. There are wide variations between the laws for licensing engineers in the different states. It is a bit disconcerting to discover that a man proclaimed by one state as an individual perfectly competent to practice engineering is, by law, wholly incompetent to practice engineering in another state.

These facts are just as important in connection with engineering education as are the characteristics of electric circuits in certain electrical engineering problems, and they may be expected to modify greatly the profession of engineering as the next generation of engineers will live and practice it. No longer will an individual be free to go his own way in a professional sense. He must meet criteria written into the law of the land; he must conform to certain requirements of the law. In short, whether we like it or not and whether we believe in it or not, the states have come or are coming to the conclusion that the public weal requires the state licensing of engineers and all that that involves; and it involves, among other things, the evaluation of the courses given in our engineering schools.

In accordance with its sovereign rights each state may set the minimum definition of an engineer for its own purposes according to its own discretion. Nothing that any outside body can do, unless our federal government finds new constitutional powers, can force a state to formulate or to adopt a definition not to its own liking. The necessity for professional guidance in the formulation of these laws is obvious.

Medical Profession Sets Example

The engineering profession may profit by the experience and activities of the medical profession which has had this problem before it for many years. That profession long ago adopted a very farsighted policy. Working through a competent and almost militant professional organization it has molded legislation and the enforcement thereof to the general good of both the profession and the public. As in the medical profession, there are great differences between the different fields of engineering practice; but the success of the national organization in those matters having to do with the educational, legal, and professional aspects of the medical profession should

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lend encouragement to a somewhat parallel organization movement among engineers.

The engineering profession has recognized differentiation very clearly, in fact too clearly. It has not seen the forest for the trees. The characteristic of engineering is the universal use of the engineering method. It is the common bond between engineers. Specialization consists only of the application of this method to certain specific types of problems. The history of engineering gives many examples of engineers of such superlative mentality that they were capable of using this method in many of, if not all, the different fields of engineering specialization. It is important that the engineering profession should act in a unified way, both as individuals and as differentiated groups. Differentiation into groups is purely a matter of convenience or a concession to limited mentality; certainly it is not at all fundamental. A comprehensive national organization of the engineering profession is not only possible but essential. Such an organization must exist and function effectively if the engineer and the engineering profession are to meet the demands of government, industry, and, in fact, social and economic progress in the immediate and distant future. The coming generation of engineers will call us remiss if they do not find such an organization ready to their hands.

Many practicing engineers are so busy with daily problems that they do not have time to mix with and obtain the views of those who shortly will replace them. There has appeared recently a very marked change in the viewpoint of the younger men. They no longer are satisfied to enter an unorganized profession functioning only through a member of specialized national societies. They insist that the profession shall be organized in such a way that it can function as a unit in those matters having to do with its social and economic problems. Although history shows us that in many respects the ideas and ideals of youth become very similar to those of the older generation, as experience is acquired, it also shows that there are significant differences between generations. The recognition of the need for a comprehensive national organization appears to be one of the ideas that the younger generation will carry over with it.

Formation of E.C.P.D.

Recently there has been formed a joint body known as Engineers' Council for Professional Development. It was organized to fill the need for a joint engineering body that could represent the engineering profession properly and effectively with respect to certain types of problems and activities. Space does not permit detailing these causative phenomena, but 5 of the most outstanding ones are enumerated briefly.

1. There was, for example, the very insistent demand of the younger generation of engineers already mentioned.

2. There was a feeling on the part of certain farsighted men connected with the state licensing of engineers that the engineering profession could and should coöperate in the formulation of criteria and methods to be used by those licensing boards. These men, themselves engineers of attainment and with high ideals for the engineering profession, feared that state licensing boards and practicing engineers might not coöperate on problems demanding joint action for the good of the public and of the profession.

3. The third driving force was the realization by engineering educators of the significance of some of the powers that had been given state licensing boards. These boards, acting independently, were empowered to compile lists of accredited schools of engineering. Certain early attempts at such activities by some of the boards caused consternation among a few of our best known engineering educators.

4. Further, industry and the nation at large were recognizing more and more the need for the development of engineers who, while well trained technically, should also be more broadly educated so that they possessed knowledge and ability in other fields of human history and activity. The leaders in such thought recognized that the production of well rounded engineers would involve more than a mere college education, good as that might be made. They conceived the necessity for a nation-wide organization that could guide men in postgraduate self-education. They recognized the probability that in the course of time such broadening study might well become a prerequisite to acceptance into the profession as a fully competent engineer.

5. Finally, certain engineers prominent in the affairs of different engineering societies had become convinced that there existed a real need for a joint body to represent the engineering profession as a whole in matters having to do with the educational, legal, and professional aspects of the engineer's life.

The E.C.P.D. was formally organized by the American Society of Civil Engineers, American Institute of Electrical Engineers, The American Society of Mechanical Engineers, American Institute of Mining Engineers, American Institute of Chemical Engineers, Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners.

Program and Activities of E.C.P.D.

This joint body consists of representatives named by the parent organizations. It has delegated powers only; that is, it is not authorized to act until instructed by the parent bodies. It constitutes an instrumentality through which the engineering profession, considered in its broadest aspect, not only may express its opinions and desires, but also may become effective in action. It gives the engineering profession a reason for uniting. It does not detract any powers from any existing organization; it does not propose to do so.

The immediate program of E.C.P.D. is briefly:

1. Proper selection and guidance of prospective engineering students.

2. Development and maintenance of proper and effective curriculums in schools of engineering.

3. Effective guidance in such postgraduate, self-education as is deemed necessary to produce a well rounded engineer. Incidentally, provision also is made for the guidance and assistance of those who desire to study engineering without attending a recognized school of engineering.

4. Coöperative agreement upon and enforcement of the degrees of achievement or accomplishment that should be attained by an individual as he mounts the rungs of the ladder leading to the status of a full fledged engineer.

In spite of the simplicity of these statements, and of the essential simplicity of the aims themselves, the actual conduct of the program is fraught with great difficulties. By no means the least springs from the individualistic characteristics of the engineer and of existing institutions. He and his insti-

tutions give ready lip service to the program that these institutions already have approved in a general sense, but the units of that program are not always considered as parts of a whole; they sometimes are considered only in their effect upon some conventional thought process or some existing way of doing things. This is but human and is to be expected. But, one might be sufficiently idealistic to hope that the engineer who prides himself on the recognition of fact and upon clear and impersonal thought could rise above such petty considerations to view matters of this sort in the light of the profession as a whole and of the advancement of the profession.

An example may serve to illustrate the sort of difficulty referred to. After lengthy and careful consideration E.C.P.D. decided to recommend that it be authorized to prepare and maintain a list of accredited engineering schools. This recommendation was made by duly accredited representatives from the professional engineering societies, from S.P.E.E. and from the national organization of state boards of engineering examiners so that all parties in interest are represented. The recommendation indicates it to be the considered judgment of these individuals that such a centralized and representative body as E.C.P.D. should accredit these schools. Now what happens when this recommendation is received by the parent bodies whose favorable action is required before any active work can be undertaken? Is there the universal recognition of facts to be expected from engineers and the consideration of the subject in the light of those facts and in a broad way? On the contrary we find in some cases a very human tendency to ignore the broader question and to concentrate upon details. The facts of the matter are that the state engineer licensing boards must prepare lists of accredited schools; the national organization of the members of these boards must prepare such a list. These men and the national society devoted to engineering education have said through E.C.P.D. to the engineers of the country, "Here is a task which merits the best judgment of all of us. We must have such lists. We would prefer that we arrive at them coöperatively. We invite your help." Would it not be most in the line of engineering thought to recognize that there is to be such accrediting and that it probably will be done best by coöperation?

No one really knows the best method to use in accrediting engineering curriculums, but the author maintains that discussion of the method to be used properly comes after a decision regarding the major proposition. Certain costs are involved, but this fact need not preclude the approval of the general principle subject to a later satisfactory solution of the problem of defraying those costs. Is not the question very simply this: If there must be accrediting, should engineers recognize the desirability of national accrediting by a most representative body, or should the matter drift until there are almost innumerable lists, differing widely among themselves and serving the individual purposes of small and disconnected bodies? There is but one answer: The engineer stands for organization properly set up and smoothly functioning. The alternative of favorable action in this case leads to the worst kind of disorganization or, at least, lack of organization.

Permanent Value of E.C.P.D.

The formation of E.C.P.D. is an almost spontaneous recognition of a radical change in the status of the engineering profession. It is the culmination of many more or less obscure movements which combined toward the formulation of a comprehensive national organization of engineers representing the educational, legal, and professional aspects of the engineer's life. Its formation does not represent a consciously planned march of an organized army across country. Instead it suggests the rather blind, instinctive concentration upon a central point by small groups coming from all possible directions. It is probable, therefore, that E.C.P.D. is not a temporary creation set up to meet a seeming need of the moment, but that it is in reality an instrument, still imperfect, for meeting a real and permanent need of our social and economic structure. It is demanded by our social evolution. It might have been initiated differently; it might have been constituted differently; its program might have been worded differently; but it was inevitable.

The organizing of E.C.P.D. is the first step in preparing matters for the coming generation of engineers. The world is becoming conscious of the social and economic significance of engineering as never before. It is already demanding a greater responsibility on the part of the engineer for the changes that his works have brought about; and, in very plain language, it finds a dearth of engineers trained and experienced to carry the responsibilities that the world desires to place upon their shoulders. The engineering profession has arrived at the point corresponding to the place in the medical profession where the witch doctor is replaced by the student of anatomy, pathology, and drugs, but the stage of public health officers and of public sanitation has not yet been reached. Engineers can handle individual engineering problems, but are not prepared to accept their share of national responsibility in the further evolution of the social and economic structure that they are influencing more and more.

The writer does not refer to the depression out of which we appear to be emerging and to the causes thereof, but to a process that has been going on for several centuries and has been particularly active in the past half century. Lawyers, military men, and business men still are wrestling with problems that engineers have created. This is not because these men are preëminently fitted for such tasks. They themselves frequently admit this. They are required to carry a disproportionate share of the burden because hitherto the engineer has not deemed it necessary to prepare himself to share such burdens.

As a comprehensive national organization, E.C.P.D. represents a very reasonable starting point, and the governing bodies of its parent organizations should become thoroughly cognizant of its aims and activities. If these governing boards can do this, no essential difficulty will be placed in the way of carrying through this epoch-marking movement.

The "Compandor"— An Aid Against Radio Static

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One of the important conditions that must be met by any speech transmission system is that it should transmit properly a sufficient range of speech intensities. In long wave radio telephony, even after the speech waves are raised to the maximum intensity before transmission, there remain energy variations such that weak syllables and important parts of strong syllables may be submerged under heavy static. The "compandor" is an automatic device which compresses the range of useful signal energy variations at the transmitting end and expands the range to normal at the receiving end, thus improving the speech-to-noise ratio. This paper deals with some of the fundamental characteristics of speech waves and explains how the task of changing them for transmission over the circuit and restoring them at the receiving end is accomplished.

WHEN the original New York-London long wave radio-telephone circuit was designed, it was recognized that radio noise would often limit transmission, especially for the weaker voice waves. Accordingly, provision was made for manually adjusting the magnitude of the speech waves entering the radio transmitters to a value that would load these transmitters to capacity.[1] Although this treatment was very effective in improving the average speech-to-noise ratio and in preventing the strong peaks of speech from overloading the transmitter, it was, of course, unsuitable for following the rapidly varying amplitudes of the various speech sounds.

The total range of significant intensities applied to the circuit is in the order of 70 db, an energy ratio of 10 million to 1. The manual adjustments already referred to were successful in reducing this range to about 30 db. To reduce further this residual range an interesting device called the "compandor" has been developed. This device, which works automatically, makes a further reduction of one-half in the residual db range so that the range transmitted over the circuit then is only 15 db, an energy ratio of about 32 to 1. Advantages gained through the use of the "compandor" may be summarized as follows:

1. The allowable increase of about 5 db in noise before reaching the commercial limit increases the time when the circuit can be used for service. The increased circuit time is greatest in the seasons of the year when it is needed the most.

2. For conditions of moderate disturbances now classed as commercial, a reduction of the noise transmission impairment to very low values is accomplished by the compandor.

3. The improvement in the operation of voice controlled relays results in delivering substantially higher volumes to the subscribers.

4. The beneficial effect of the compandor might alternatively be applied to a reduction of transmitted power.

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Speech Energy

Quantitative designation of speech intensity, and hence of a range of intensities is rendered difficult by the rapidly varying amplitude characteristics of the various speech sounds. Devices called volume indicators are used fairly extensively to indicate the so-called "electrical volume" of speech waves. (The term "volume" will be used through the rest of this paper to designate this quantity and not as synonymous with loudness.[2]) A volume indicator is essentially a rectifier combined with a damped d-c indicating meter on which are read in a specified manner the standard ballistic throws due to partly averaged syllables at a particular speech intensity. These devices are so designed and adjusted that they are insensitive to extremely high peak voltages of short duration, but their maximum deflection is approximately proportional to the mean power in the syllable. It has been found that, if commercial telephone instruments are used, the ear does not detect amplifier overloading of the extremely high peaks of short duration. Consequently, the volume indicator is a useful device for indicating the noticeable repeater overloading effect of a voice wave. These devices do not reveal much about the effect of the weaker voltages in overriding interference or operating voice-operated devices but they give a fairly satisfactory indication of loudness and possibilities of interference into other circuits.

The sound energy that the telephone transmits consists of complicated waves made up of tones of different pitch and amplitude. The local lines and trunks connecting the telephone to the subscribers' toll switchboard have little effect in changing the fundamental characteristics of these waves but, on account of various amounts of dissipation, the waves received at the toll switchboard always are weaker than those transmitted by the telephone. Furthermore, the strength of signals varies with the method

of using the telephone, loudness of talking, battery supply, and transmitter efficiency. The subscriber may be talking over a long distance circuit from a distant city, in which case the loss of the toll line further attenuates the received waves. The curve in Fig. 1 (plotted on so-called "probability paper," in which the scale is such that data distributed in accordance with the "normal law" will produce a straight line) shows that the range of outgoing speech volumes as measured by a volume indicator at the transatlantic switchboard at New York is nearly 40 db for terminal calls. When via calls and variation in volume of the individual talker are taken into account, it is even greater than 40 db.

Volume Range of a Telephone Circuit

There are 2 limits on the range of volumes which a system can transmit. The upper limit of volume is set by the point at which overloading appreciably impairs the signal quality or endangers the life of the equipment. It is an economic limit set by the cost of building equipment of greater load capacity.

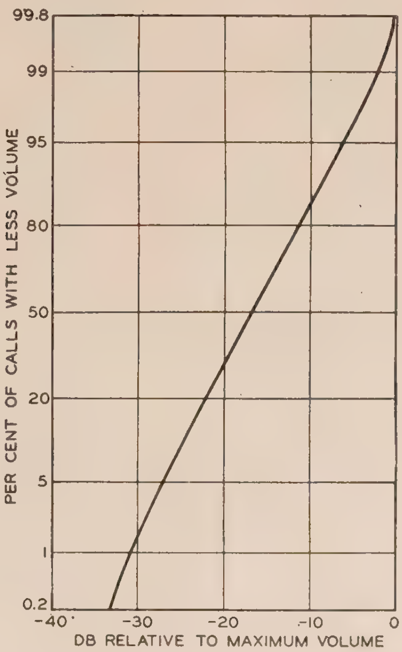

Fig. 1. Range of outgoing speech volume of 950 local subscribers at New York transatlantic switchboard as measured from January to April 1931

The lower limit of volume is set by the combination of the amount of attenuation and the amount of interference in the system such that the signal should not be masked appreciably by noise. This also is ordinarily an economic problem depending on the cost of lowering the attenuation or of guarding against external interference. In some cases, however, this limitation is a physical one. A striking case is that of radio transmission in which there is no means of controlling the attenuation of the electromagnetic waves in transit to the receiving station. They may arrive at levels below those of thermal[3,4] noise in the antenna and other receiving apparatus. Thus, even in the absence of static, there is a definite useful lower limit to the received and hence the transmitted volume. In such cases the problems raised by the spread in signal intensities become a matter of particular importance. Radio telephony, therefore, was one of the fields of use particularly in view for the development of the device to be described.

Effect of Volume Control

Until recently the only method in use for reducing the range of signal intensities on radio circuits was a special operating method for constant volume transmission. At each terminal the technical operator, with the aid of a volume indicator, adjusted the speech volume going to the radio transmitter to that maximum value consistent with the transmitter load capacity.

In Fig. 2 is shown the normal relation of input to output intensities of a zero loss transducer as given by the diagonal line. Points A_{max} and A_{min} on this line indicate the extreme values of signal intensities for sustained loud vowels covering a volume range of 40 db. The effect of the volume adjustments made by the technical operator is to bring all the applied volumes to a single value indicated by point B. The value of B could be any convenient intensity. Here it is set at a value determined by transmission conditions in the line between the technical operator's position and the radio transmitter.

As the technical operator has reduced the strongest volumes 5 db and increased the weakest volumes 35 db, the result of this volume control is to increase the volume range which the circuit can handle by 40 db. Through the use of voice controlled switching arrangements[5] which permit transmission in only 1 direction at a time, it is possible to make this adjustment for 2-way transmission in the case of radio circuits without danger of singing. By this method of operation, volumes initially strong or weak are

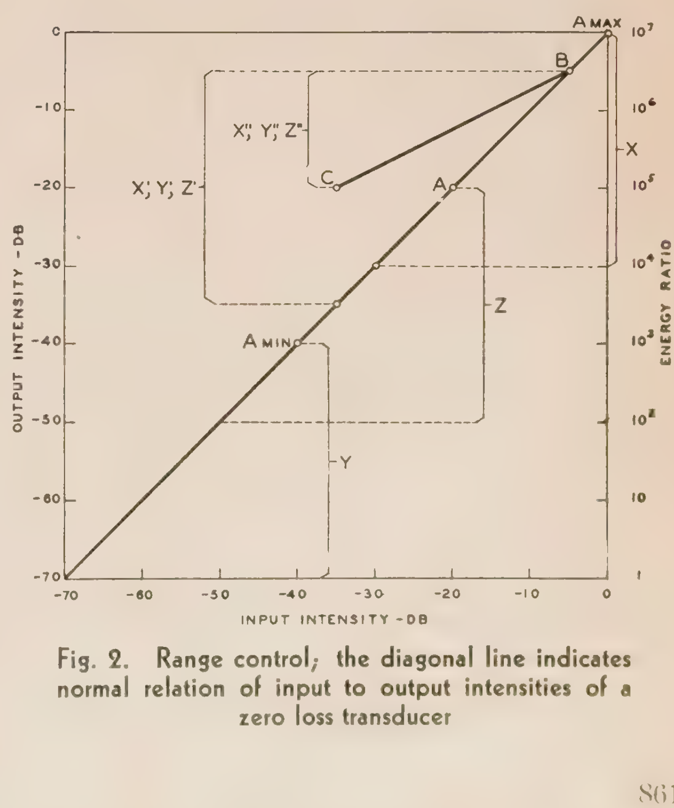

Fig. 2. Range control; the diagonal line indicates normal relation of input to output intensities of a zero loss transducer

delivered to the distant receiving point with equal margins relative to interference and the transmission capacity of the whole system is improved thereby.

Intensity Range at Constant Volume

However, even with speech adjusted to constant volume at the transmitting point, there are large variations in signal intensity from syllable to syllable and within each syllable. For example, the energy of some consonants as compared with the stronger vowels is down about 30 db. The importance of the weaker sounds is brought out by the fact that in the case of commercial telephone sets a steady noise 30 db below the energy in the strongest parts of the speech syllables produces an appreciable impairment in transmission efficiency. Accordingly, it is desirable to maintain transmission conditions such that generally more than this range is kept free from the masking effect of noise. This range of intensities within the syllable also is of importance in the operation of the voice controlled switches used in the radio system. The sensitivity spread between a voice operated relay which just operates on the crests of loud syllables and one which operates sufficiently well not to clip speech also is about 30 db.

Considering that in Fig. 2 the coördinates are in terms of the average rms value over a period of time small compared with the time of a syllable, there is a spread of at least 30 db in signal intensity extending down from the maximum for each talker. Thus for the weakest talker this spread is indicated by the bracket Y and for the strongest, by X. Any other talker, as Z, falls somewhere in between. After manual control of volume this spread of intensities is represented by the bracket X', Y', Z' for all talkers. This residual spread makes desirable a means for further compressing the range of intensities in the speech signals so that the weaker parts of sound are transmitted at a higher level without at the same time raising the peak values of speech and so overloading the transmitter.

Types of Compression Systems

This problem can be approached in several ways. One, for instance, is from the frequency distortion standpoint. As many of the weaker consonants have their chief energy contribution in the upper part of the speech band, a simple equalizer which relatively increased the energy of the higher frequency consonants before transmission and another which restored the frequency energy relations after transmission should be found of value. Tests have confirmed this expectation to some degree. Unfortunately, the best type of equalizer depends upon the type of subscriber station transmitter, so that in general only a compromise improvement can be obtained.

Another general method of approach is that of amplitude distortion in which the weaker portions of the syllable are automatically increased in intensity in some inverse proportion to their original strength. The manual control of volume described may be considered the genesis of this method. Early suggestions[6] included the use of an auxiliary channel such as a telegraph channel for duplicating the control operations in the reverse sense at the receiving end, thus restoring the original energy distribution. Another early suggestion along this line was made by George Crisson of the American Telephone and Telegraph Company.[7] If a voltage be applied to a circuit consisting of a 2-element vacuum tube (with a parabolic characteristic) in series with a large resistance, the instantaneous voltages across the tube are approximately the square root of corresponding voltages applied. Thus a voltage originally 1/100 the peak voltage can be transmitted at an intensity of 1/10 the peak, or 10 times its original intensity. If the instantaneous energy is expressed on the logarithmic or db scale the energy range is then cut in half. Such a device may be called an instantaneous compressor. At the distant end a circuit that is simply the inverse of that at the transmitting end is used. The output voltage is taken off of a low resistance in series with a parabolic element, thus restoring the signal substantially to its original form. This circuit may be called an instantaneous expandor. This scheme was tested successfully in the laboratory, but unfortunately possesses a very serious limitation for practical application in the telephone plant. This is due to the fact that, to maintain properly the characteristics of the compressed signals, a transmission band width without appreciable amplitude or phase distortion of about twice the normal proved necessary.

The "Compandor"

The principle of the present device is the use of a rate of amplitude control for the compressing and expanding devices intermediate between manual and instantaneous control, which may be considered approximately as a control varying as a function of the signal envelope. Such a modulation of the original signal in terms of itself does not appreciably widen the frequency band width of the modified signal as compared with the original signal. The transmitting device is called the compressor; the receiving device, the expandor; and the complete system, the "compandor."

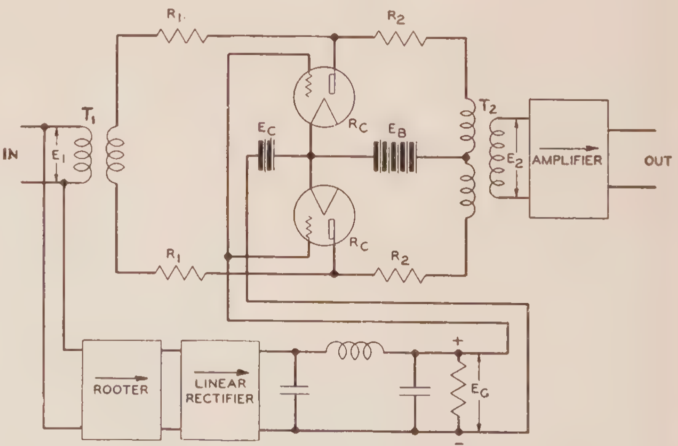

Fig. 3. Compressor circuit No. 1

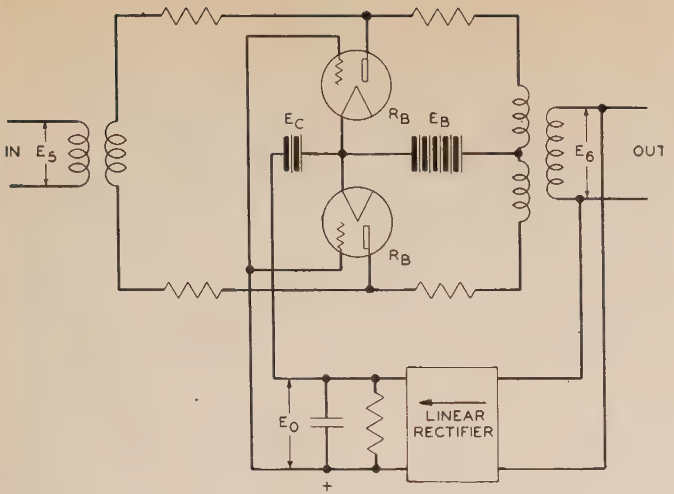

Fig. 4. Compressor circuit No. 2

The functional behavior of a typical compressor may be considered with reference to the simplified schematic circuit No. 1 of Fig. 3. This circuit is of the forward acting type; that is, the control energy is taken from the line ahead of the point of variable loss. The variable loss consists of a high impedance pad connected in the circuit through 2 high ratio transformers T_1 and T_2. The high resistances R_1 and R_2 are shunted by a pair of control tubes connected in push-pull. The push-pull arrangement is desirable for 2 reasons. It reduces the even order non-linear distortion effects caused by the shunt path on the transmitted speech and it balances out the control impulse and unfiltered rectified speech energy from the control path which might otherwise add distortion to the speech. The impedances of these tubes are controlled by the control voltage E_G which is roughly proportional to the envelope of speech energy and which is derived from the line through a non-linear or "rooter" circuit (so-called because the output is proportional to a root of the input, see eq 4), a linear rectifier and a low-pass filter which may have a cutoff frequency in the range 20 cycles to 100 cycles. In the following analysis it is assumed that the delay due to this filtering is negligible.

Let E_1 = rms speech voltage at input
and E_2 = rms speech voltage at output in same impedance
R_C = a-c impedance of control tubes.

Now if R_C is kept small compared to the pad impedance, we have approximately

$$E_2 = k_1E_1R_C \tag{1}$$

Let E_G be the control voltage applied to the grids of the control tubes. With the plate voltage E_B just neutralized by the steady biasing grid voltage E_C, then only E_G may be considered as determining the space current and we may assume ideally that the space current

$$I_B = k_2 E_G^{s}$$

$$\text{Then } R_C = \frac{dE_B}{dI_B} = \mu \frac{dE_G}{dI_B} = \frac{1}{k_3E_G^{s-1}} \tag{2}$$

where s is determined by tube design and the k's are constants for constant μ tubes. For variable μ tubes eq 2 can be used to set requirements on the tube design. From eqs 1 and 2

$$E_2 = \frac{k_1E_1}{k_3E_G^{s-1}} \tag{3}$$

Now let the rooter be a non-linear circuit such that the instantaneous voltage is the t^{th} root of E_1. After rectification and filtering we will have approximately

$$E_G = k_4E_1^{\frac{1}{t}} \tag{4}$$

From eqs 4 and 3 we have

$$E_2 = \frac{K E_1}{E_1^{\frac{s-1}{t}}} = K E_1^{\frac{t-s+1}{t}} \tag{5}$$

If $t = s = n$

$$E_2 = K E_1^{\frac{1}{n}} \tag{6}$$

Now if the input voltage be increased by a factor x, the input increment in db will be 20 log x. The new output will be

$$E_2' = K(xE_1)^{\frac{1}{n}}$$

The increment in output in db will be

$$20 \log \frac{E_2'}{E_2} = 20 \log x^{\frac{1}{n}} = \frac{20}{n} \log x$$

The ratio of the output increment to the input increment in db is $\frac{1}{n}$ and the device is said to have a compression ratio of $\frac{1}{n}$. In other words, the per cent change in relative speech voltages in passing through the compressor is the same at all points in the intensity range. In the general form of this circuit t and s need not be equal to secure a particular value of $\frac{1}{n}$.

In Fig. 4, compressor circuit No. 2 is shown, a backward acting type of circuit. In this circuit the control tubes can be used to perform the function of the rooter in circuit No. 1 when $s = t = n$. We may write for this circuit

$$E_6 = k_1E_5R_B$$

$$E_0 = k_2E_6$$

$$R_B = \frac{1}{k_3E_0^{n-1}} = \frac{1}{k_4E_6^{n-1}}$$

$$E_6 = \frac{k_1E_5}{k_4E_6^{n-1}} = KE_5^{\frac{1}{n}} \tag{7}$$

which is the same as eq 6 for circuit No. 1.

In Fig. 5 is shown the expandor circuit. If the resistances r are kept small compared with those of the control tubes, we may write

$$E_8 = \frac{k_1E_7}{R_x}$$

$$E_x = k_2E_7$$

$$R_x = \frac{1}{k_3E_x^{n-1}} = \frac{1}{k_4E_7^{n-1}}$$

$$E_8 = KE_7E_7^{n-1} = KE_7^{n} \tag{8}$$

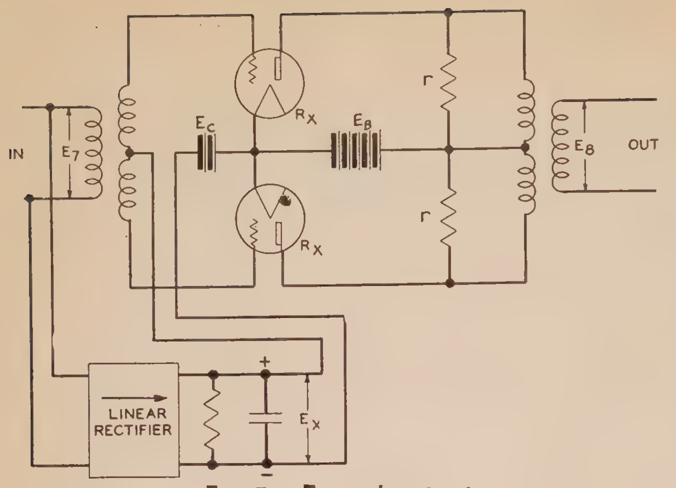

Fig. 5. Expandor circuit

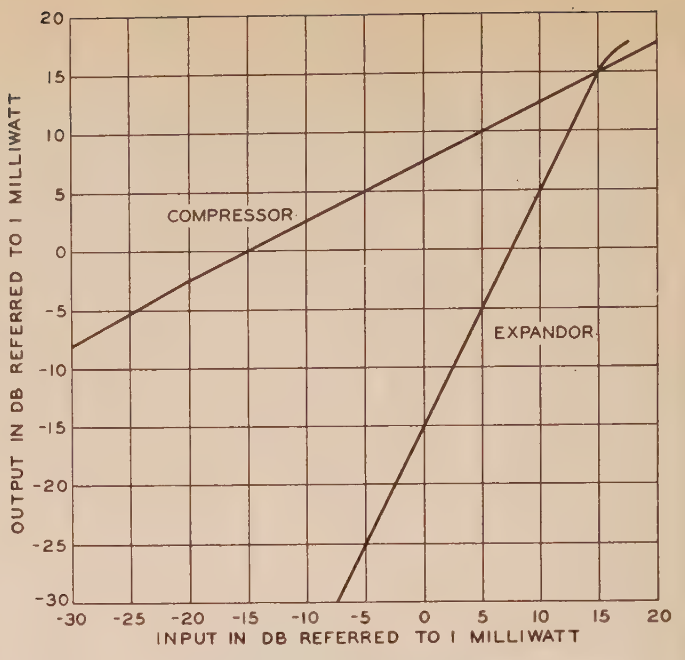

Fig. 6. Experimental input-output characteristics; 1,000 cycles steady state

This relation is just the inverse of that given in eqs 6 and 7. The increment ratio in db of output to input is n and the expansion ratio may be said to be n. When a compressor and expandor having the same value of n in their indices are put in tandem, the final output and input intensity ranges are the same. However, between the compressor and expandor the range of signal intensities, whose rate of change is not faster than the usual syllabic envelope, is $1/n$ in terms of db. In terms of voltage ratios the intermediate signal intensities are proportional to the square root of their original values if $n = 2$, the cube root if $n = 3$, etc.

The ideal relations postulated above cannot all be met in the physical design of the circuits. The indices s and t must be the dynamic characteristics of the tube and circuit and can be held to constant value only over limited ranges of operation. Equation 2 is only approximately true as some space current is permitted to flow when no speech is passing; otherwise, impractical values of control impedances would be involved. However, they do serve to illustrate the functional operation and can be approximated sufficiently well in commercial equipment for useful amounts of compression and expansion. Fig. 6 shows experimental steady-state input versus output characteristics for devices built to have a compression ratio of $^1/_2$ and an expansion ratio of 2.

The compressor is seen to operate substantially linearly over a 45-db range of inputs and the expandor over a 22.5-db range. This is about as much range as can be secured conveniently from a single stage of vacuum tubes. As such ranges would be entirely insufficient to handle the seventy odd db range at speech intensities, it is necessary to control volumes to a given point before sending through these devices, rather than compress or expand first and then control. The range is adequate, however, to take care of the range of signal intensities for commercial speech at constant volume.

Effect of Compandor

The compressor curve of Fig. 6 indicates that, when the input is 15 db above 1 milliwatt, the compressor gives no gain or loss. If the levels are adjusted so that this point corresponds to the intensity at point B on Fig. 2, then the line BC indicates the compressed intensities corresponding to the assumed 30 db spread of speech controlled to constant volume. The new range of intensities as indicated by the bracket X'', Y'', Z'' is now finally reduced to about 15 db. Tests show that a volume indicator on the output of the compressor reads from 1 to 2 db higher than on uncompressed speech at its input. Compressed speech sounds slightly unnatural but the effects of compression upon articulation in the absence of noise are negligible.

In considering the action of the expandor it is important to note that all of the improvement in signal-to-noise ratio is put in by the compressor. Considering any narrow interval of speech the insertion of the expandor does not change the signal-to-noise ratio. The desirability of using it depends on other reasons. First, it restores the naturalness of the speech sounds. Second, the apparent magnitude of the noise is greatly reduced since noise comes in at full strength only when speech is loudest and is reduced by the loss introduced by the expandor at times when the energy is low between syllables. When no speech is being transmitted, noises up to a certain limit, which corresponds to the maximum energy in received speech, are reduced in varying amounts from about 20 db to zero depending on their value.

When speech is present the effect of the expandor is determined by the sum of the instantaneous speech and noise voltages, so that the effect on the noise, whether it is large or small, is determined largely by the existing speech intensity. For a circuit having somewhere near the limit of static, the use of the compandor allows on the average 5 db more noise than when it is not used. When the noise is less than this limit, somewhat greater improvements are

obtained from the compandor, ranging up to at least 10 db.

The particular values of compression and expansion ratio were chosen initially for the relative ease in the design of the system with commercially available vacuum tubes whose characteristics closely approximated a parabola. Tests of the equipment have shown that this degree is sufficient for present telephone circuit intensity range requirements. Increasing the amount of compression is limited by increase in quality distortion and by increased variation in the intensity of radio noise as heard by the listener. A noise which is constant at the input to the expandor varies on the output as the speech intensity changes. Also variations in attenuation equivalent between the compandor terminals are multiplied by the expandor. Herein lies a reason for having a constant compression and expansion ratio over the working range. If it were different at different intensities, attenuation changes would distort the reproduced speech as well as appearing as a somewhat increased change in intensity. This change in intensity is n times the attenuation change in front of the expandor in db.

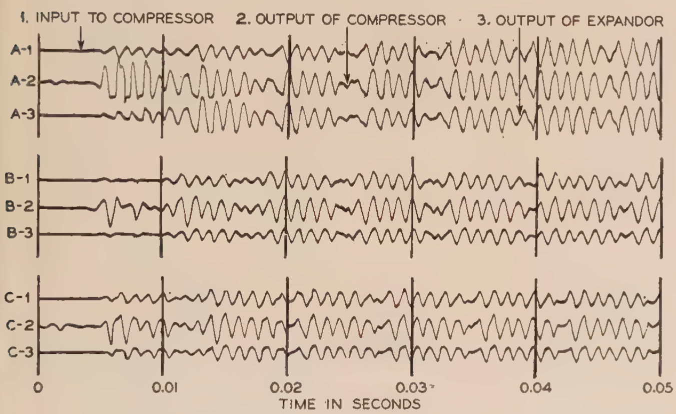

Fig. 7. Oscillograms showing operation of compandor on beginning of word "bark"

A—Compressor circuit No. 1
B—Compressor circuit No. 2 with low pass filter in control circuit
C—Compressor circuit No. 2 without filter

The degree of compression obviously may be controlled in a variety of ways; such as using different values for the indices s and t, applying control voltages upon more than one variable stage in tandem, the use of variable μ vacuum tubes, etc. The circuits as shown use variable shunt control for the compressor and variable series control for the expandor. Either or both may be changed to the other by inverting the polarity of the control potential and properly designing the rectifier characteristics of the control circuits.

There are 2 major sources of possible speech distortion that must be considered in the design and use of these devices in addition to those ordinarily present. The first is due to the non-linear characteristics of the vacuum tubes used for controlling. The even order distortion terms are largely balanced out by using 2 tubes in a push-pull arrangement. The remaining distortion is minimized by having speech pass through the control tubes at a sufficiently low level. In the operating ranges for the device shown in Fig. 6, the harmonics of a single-frequency tone are 30 db or more below the fundamental.

The second major source of distortion is the time lag in the control circuits due to the presence of the filters after the linear rectifier. However, with a complete compandor circuit using the compressor circuit No. 1, it was found on careful laboratory tests with expert listeners that it was almost impossible to distinguish whether the device was in or out of circuit. Furthermore, distortion of this type is largely eliminated when compressor circuit No. 2 is used. In that case it may be noted that, if both terminals are connected by a substantially distortionless transmission system, the identical control circuits of both devices receive identical operating voltages. As the gain changes put in are reciprocal and occur now with equal time lag, the deviations from ideal compression are virtually counterbalanced by the inverse deviations from ideal expandor action. In Fig. 7 are shown oscillograms taken of the first part of the word "bark." Each record shows the intensity changes before the compressor, between the compressor and expandor and on the output of the expandor.

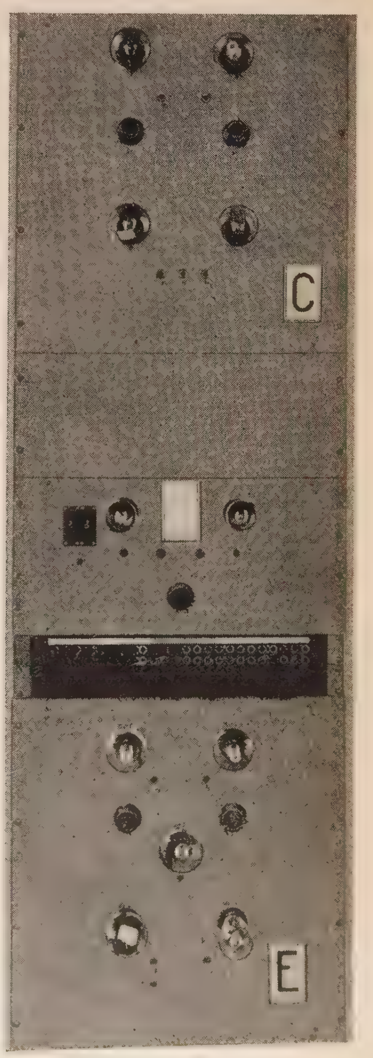

Fig. 8. Experimental installation of compandor at New York

Application to Transatlantic Circuit

A compandor system has been in service on the New York-London long wave radio telephone circuit since about July 1, 1932. At first compressor circuit No. 1 was used, and later a change was made to compressor circuit No. 2. In Fig. 8 is shown the experimental installation at New York. It occupies about 5 ft of standard relay rack space. The blank panel shown indicates the saving of apparatus resulting from the change to compressor circuit No. 2.

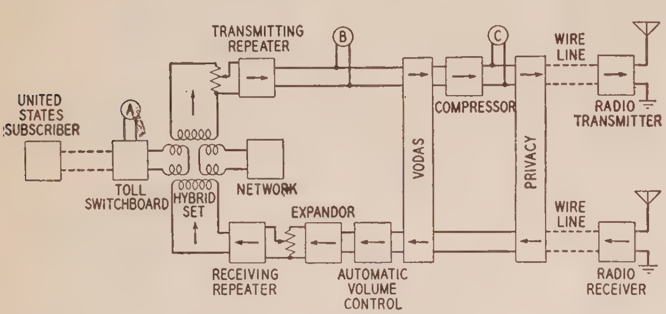

Fig. 9. Compandor applied to one end of a radio telephone circuit

The schematic diagram of Fig. 9 shows the method of inserting the compressor and expandor in the radio telephone terminals at each end of the circuit. Since the 2 ends are similar, only one end is shown. The compandor circuits are indicated in their relation to the subscriber, the toll switchboard, the vodas and privacy apparatus, and the radio transmitter and receiver.[5] A meter located at the point designated *A* would indicate the full range of applied volumes, at *B*, the controlled volumes and at *C*, the compressed speech signals.

When the United States subscriber talks, electrical waves set up by his voice pass over a wire line to the toll switchboard. They then divide in a hybrid set; part of the energy is dissipated in the output of a receiving repeater and part is amplified by a transmitting repeater whose gain is controlled by noting the reading of a volume indicator at *B* and adjusting a potentiometer ahead of the transmitting repeater. The waves then act on the vodas which consists of amplifier-detector, delay circuit and relays for switching the transmission paths in such a manner as to prevent echoes, singing, and other effects. When in the transmitting condition, the vodas is arranged to have zero loss so that the waves impressed on the compressor are practically the same as at *B*. The waves put out from the compressor are then sent through the privacy apparatus, the output of which is then sent over a wire line to the radio transmitter. The radiated waves are picked up by the distant radio receiver, amplified and transformed into voice-frequency energy which passes over a wire line to the terminal at the distant end.

The path of received waves in either terminal may be traced in the lower branch of the circuit shown in Fig. 9. After being made intelligible by passing through the receiving privacy device, the compressed incoming waves are sent through the vodas into an automatic volume control and then into the expandor. The expanded waves are sent through a receiving repeater from whose output the amplified waves pass into the hybrid set, part being dissipated in the network and the other part going through the toll switchboard to the subscriber. Due to imperfect balance between the subscriber's line and the network, a portion of the received energy is transmitted across the hybrid set and amplified by the transmitting repeater. This echo might operate the transmitting vodas under certain conditions. For this reason a potentiometer is inserted in the receiving branch of the circuit so as to reduce the echo, and consequently the received volume, so that false operation of the transmitting vodas is prevented.

Results of Compandor Operation

Effectiveness of the compandor in service depends not only upon its ability to reduce noise, but also upon its relation to the other characteristics of the circuit. Tests in the laboratory and on the long wave transatlantic circuit have indicated that the presence of the compandor does not affect the quality appreciably, provided compressor circuit No. 2 is employed and provided the compression in the circuit itself is not serious. Delay distortion can be tolerated up to about the same amount as when no compandor is used. Frequency changing for privacy purposes is not materially affected by the compandor.

The expandor increases the transmission variations in the circuit exactly as it increases the voltage range of the waves applied to it. It is, therefore, necessary to guard against excessive variations in the over-all circuit including the wire line extensions as well as the radio links. At the New York terminal there has been installed an automatic volume control operated from received speech signals which performs this function.

The received volume is limited by waves which do not operate the receiving side of the vodas, but which return as echoes to cause false operation of the transmitting side. The compressor increases these weak waves so that they are better able to operate the receiving side of the vodas, and the expandor effectively increases the stronger waves relative to the weak. This results in more received volume being delivered to the 2-wire terminal than when the compandor is not used. The overall improvement in volume delivered to the subscriber varies with the noise, being greatest when the noise is low.

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Recent Developments in Suspension Insulators

A recent development in the design of the cap and pin of suspension insulators, to enable compression principles of stress distribution to be incorporated, has made possible an increase from 6,000 lb to 11,000 lb in load as determined by time-load tests covering a period of 2 years. Also, fatigue failure caused by vibration has been found to occur in the metal part before the porcelain is affected.

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THE EVOLUTION of the suspension insulator has been reviewed recently before the Institute so that it is unnecessary to discuss again here the early developments and the changes in design that have produced a type of insulator embodying compression principles of mechanical load distribution for improved performance. ("Development of Porcelain Insulators," K. A. Hawley, A.I.E.E. TRANS., March 1931, p. 47.) In the design described in the following paragraph, the details of the cap and pin are so shaped as to resolve the mechanical load into compressive stresses in the porcelain, in contrast to the shear and tensile stresses in the older designs.

Design developments during recent years have notably improved the compression loading features of the porcelain and are, therefore, of general interest. The older shear and tension type of design is shown in Fig. 1a and the latest compression type is illustrated in Fig. 1b. In the latter the keystone arch and buttress principles of construction are evident, with the cap acting as the buttress, the pin as the keystone, and the porcelain as the arch. This construction offered such a decided improvement in mechanics that extensive tests were conducted over a 2-year period to determine its merits and to compare it with the previous designs. The tests and results are especially significant in view of A. O. Austin's discussion of Mr. Hawley's paper, in which he said: "Where long life and reliability are desired, low stress in the dielectric, due to the combined working load and differential expansion, is far more important than a good factor of safety for the working load based on the maximum or ultimate [strength] on test . . . the time lag before defects are apparent, together with the wide variety of conditions encountered in service, make it exceedingly difficult to predict results from design or accelerated tests."

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Virginia, June 25–29, 1934. Manuscript submitted March 5, 1934; released for publication March 16, 1934. *Not published in pamphlet form.*

Measurement of Insulator Strength

It is generally recognized that, with good porcelain, the service life of the suspension insulator depends upon the mechanics of the design in distributing the stresses of loads and thermal changes. As a check on the distribution of load stress, etc., there are the ultimate strength, the combined mechanical-electrical strength, and the time-load performance. The ultimate strength, as such, has long been superseded by the combined mechanical-electrical strength, which is a better measure of expected performance. It is used as a reference base for the latter, their ratio giving an indication of the stress balance, and in determining the mechanical factor of safety, but this is secondary to the combined mechanical-electrical strength that determines the effective limit of the insulation. In the combined mechanical-electrical strength test the time element is an important factor, as was recognized some 10 years ago by a customer's specification that called for this test at 11,000 lb for 1 min. Time and load increments similar in proportion to accelerated service conditions furnish a more comprehensive evaluation of performance and lead to the so-called time-load test.

The performance values for these characteristics are given in Table I, which also shows the comparison of the 2 designs in Fig. 1.

This improved performance with the same or slightly smaller dimensions of the porcelain head is an ample demonstration of the superior distribution of stress in the compression type. It also confirms the theory of the design and the results of the preliminary photo-elastic study of various models. The insulator has the well-known and proved resilient

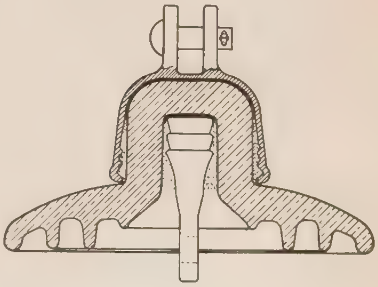


Fig. 1a. Tension and shear type design

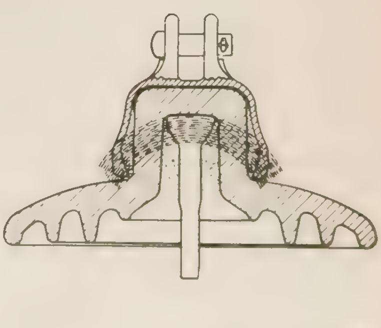


Fig. 1b. Compression type design

Table I

Types of Test	Shear Type	Comp. Type
Ultimate strength	14,000 lb	15,000 lb
Comb. mechanical-electrical	12,000 lb	15,000 lb
Time-load for 1 week	8,000 lb	13,000 lb
Time-load for 1 month	7,000 lb	12,000 lb
Time-load for 1 year	6,000 lb	11,500 lb
Time-load for 2 years	6,000 lb	11,500 lb

assembly using the sanded cementing surfaces and cushioning film. The time-load tests through several seasons of normal weather and temperature changes are an indication of the ability of the compression type to take care of thermal stresses, but a much more exhaustive and detailed investigation was made of this feature.

Effect of Thermal Changes

An analysis of the stress action under thermal changes develops the critical points in the design. The coefficient of expansion of the metal parts is approximately $2^1/_2$ times that of the porcelain. The greatest hazard is therefore where the porcelain envelopes the metal, which occurs in the assembly of the pin in the porcelain.

The insulator assembly is steam cured at a temperature exceeding that reached in usual climatic conditions. In returning to normal temperature after assembly, the metal parts shrink more than the porcelain. During subsequent temperature changes the action of the cap with increase in temperature is to expand, relieving the porcelain head of stress. This expansion and any movement of the cap remain within the limits established in the assembly during the steam curing. With decrease in temperature the action is reversed, the shrinkage of the cap tending to place the porcelain head under compression. The great strength of porcelain in compression and the greater mass of the porcelain relative to the metal in the cap, which is in tension, leave the porcelain unaffected by this change in temperature. The reduction in dimension of the cap incident to the shrinkage is compensated by the elongation under the tensile stress developed by the shrinkage against the porcelain, and movement of the cap is, therefore, negligible over the normal temperature range.

The combination of the load stress with these thermal stresses does not change the behavior of the cap to any appreciable extent. The reaction of the load between the cap and the porcelain places the head of the porcelain under compression. This action is automatically compensating, any change in load producing a corresponding change in pressure by reason of relative movement between the cap and the cement along their lubricated surfaces. These large surfaces reduce the stress per unit area to a low value and the vertical movement of the cap with normal load changes is therefore small.

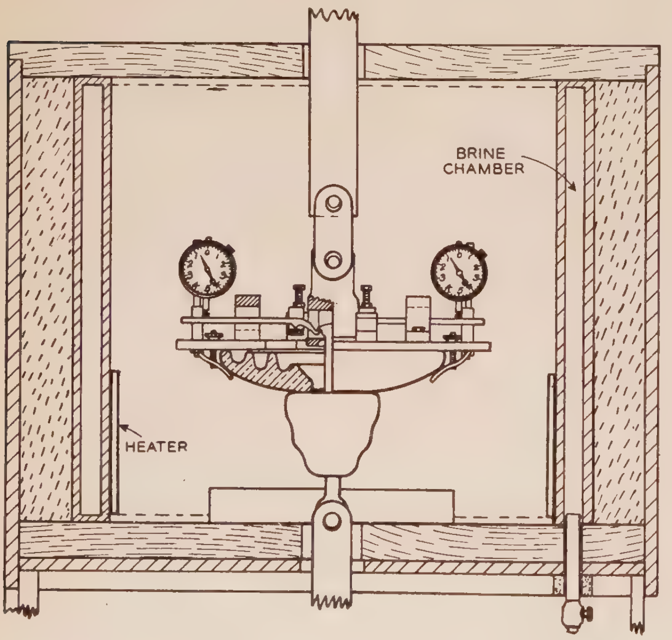
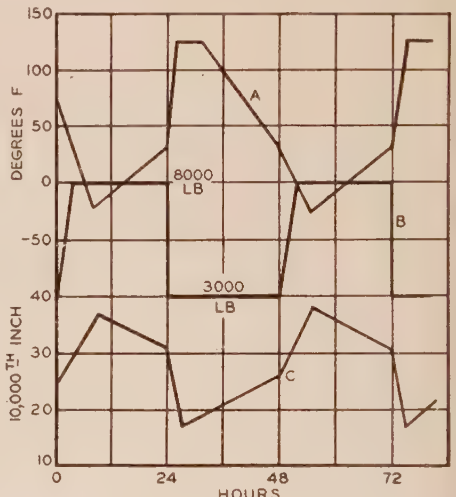


Fig. 2. Arrangement for measuring pin extension and recovery

The behavior of the lubricating material that is applied to the inside surface of the cap is an important factor, particularly in that it must function properly over wide limits of temperature. A texture and thickness of the material were determined that give the same performance at extreme as at normal temperatures. It is of interest to note that in experimental assemblies where much slippage of the cap occurred, the bell of the cap was ruptured by splitting; the porcelain was not impaired. This demonstrates that the porcelain is immune to any shear component of the cap stress caused by cap movement.

Fig. 3. Pin extension and recovery with changes in load and temperature

A. Temperature
B. Load
C. Movement



Effect of Load on the Pin

Considering the pin without load, it expands with increase in temperature but the temperature and expansion in service do not reach those attained in assembly; with decrease in temperature it shrinks

more rapidly than the porcelain. In either condition the porcelain is free from stress. The addition of load stress restricts this freedom of adjustment and introduces a more complex factor. The area of the pin head is relatively small and the stress per unit area large. The pin is, therefore, more subject to movement than the cap, and it pulls into or nests in the cement in adjusting its position under load. The worst case may be represented by a service condition where reduced temperature shrinks the pin and a sleet load added to the conductor load pulls or tends to pull the head of the pin into the cement. With subsequent increase in temperature it is important that the head recovers its normal position to prevent wedging and the resulting severe stresses.

The controlling factor in the ability of the pin to recover its position is the shape of the working cone. This part is one of the most important in the whole design. Many shapes of single-cone pins have been used in past years, all of which have the advantage of minimum mass, but were made with a straight or, with respect to the axis, a concave bearing surface. None of these shapes gives a uniform distribution of load stress over the bearing surface. Photo-elastic studies showed clearly that stress concentration occurred at the edge of the cone. This is caused by the greater displacement of that part of the cone as it moves or tends to move into the cement. The convex shape enables the improved cone to give an equal displacement for each increment of bearing surface in order to insure uniform distribution of stress and prevent any wedging action. The recovery of the pin was studied in an investigation of the cone movement between wide limits of load and temperature range. The test was arranged as in Fig. 2, the insulator being enclosed in a thermally insulated container with temperature limits obtained by circulating brine and heating elements. The load was applied by weights and levers and movement of the pin with respect to the porcelain was determined by dial measurements to 0.0001 in. and compensated for elongation and thermal change in dimensions. Starting at normal temperature with a load of 3,000 lb, the temperature was reduced to freezing; there the load was increased to 8,000 lb and the temperature reduced to −20 deg F. The temperature was then increased and at 32 deg F the load was reduced to 3,000 lb; the rise in temperature was continued to 120 deg F, and reduced to normal. This procedure constituted 1 cycle and covered a period of 48 hr. The response of the cone of the pin to the load and temperature changes for 2 cycles is illustrated by Fig. 3. The variation between maximum and minimum points of movement is fairly uniform for successive cycles and equilibrium is reached in several cycles, as indicated by Fig. 4. The leveling off of the curves of extension demonstrates that the effect is not cumulative and that progressive wedging of the pin does not occur. This figure also shows the behavior of a 3-step pin similar to the design in Fig. 1a. The degree of movement is dependent upon the pin shape, load area, and the thickness of the resilient coating over the load area. The 3-step pin with greater load area has for equal thickness of coating a lower range of movement and permanent deflection than the single cone shape. However, it is less efficient than the latter because of the larger shear component in its distribution of stress. The permanent deflection or set under the 3,000-lb load is represented by the line of minimum extension. This is attributed to the minute migration or compression of the resilient coating against the surface of the cement column by the seating of the cone. Tests on various sizes of the single cone design showed that difference in size does not alter the recovery movement, and that the pin adjusts itself to severe service conditions so that the assembly is protected from injurious stresses.

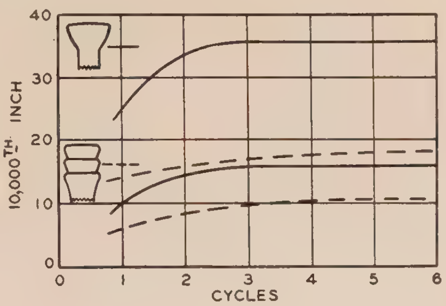


Fig. 4. Maximum and minimum limits for extension and recovery

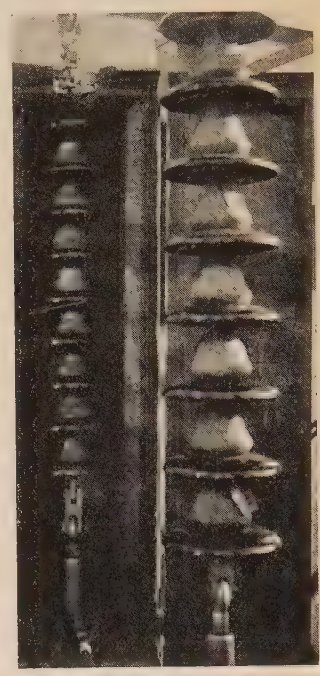


Fig. 5. Steam chest for heating insulators on time-load test

Recognizing that the seating of the cone imposes additional stress, a further check on the effect of combined load and thermal changes was made by subjecting insulators on time-load test to a wide temperature range. A string of insulators carrying a load of 10,000 lb was enclosed in a steam chest, shown by Fig. 5, in which it was heated to 150 deg F during the day, and then was exposed to freezing and subzero weather conditions at night. Retention of the constant high load over the temperature range imposed caused unusually severe stress conditions, and repeated cycles of this treatment without insulator

failure demonstrated the uniformity of stress distribution and adjustment to differential expansion.

Effect of Vibration

Another feature investigated on time-load test was the effect of vibration and load oscillation. A device shown in Fig. 6 was added to the loading arrangement to oscillate the load at the rate of approximately 115 cycles per min between the limits of 6,500 and 10,500 lb, thus also inducing considerable vibration in the insulator string. This test proved to be more destructive to the equipment and metal fittings than to the insulators. Repeated failures occurred in the fittings as the number of cycles approached 300,000, but there was none in the insulators. This performance has been paralleled in more recent tests made by a cable manufacturer on accelerated cable vibration in which suspension insulators were used to support the cable, and where failure occurred in the metal attachment, the porcelain remaining undamaged. The results of these tests indicate that the porcelain is less susceptible to vibration than the connecting hardware, and they also confirm our research findings that the fatigue strength of porcelain is at least 80 per cent of static strength in comparison to approximately 60 per cent and less for metals.

The results of these tests are believed to be the best indication of service performance available at the present time. The effect of vibration and of wedging of the pin long have been topics of varying opinion and the results of the observations on these therefore are of special interest. The time-load test is inherently a natural basis for measuring service performance, as the degree to which load and temperature variations can be accelerated without insulator failure constitutes a measure of comparative merit. The performance on all of the tests demonstrates the improvement obtained with the latest design development.

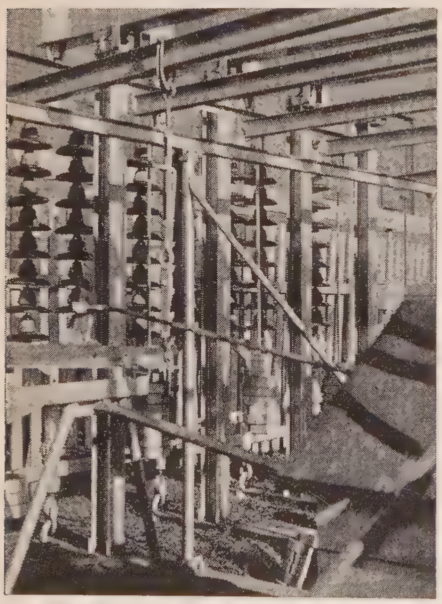


Fig. 6. Arrangement for vibrating and oscillating the load on insulators on time-load test

Factors Influencing the

Insulation Coördination of Transformers—II

Supplementing a previous paper, data given here verifies the coördination between transformer major insulation and standard edge gaps for surges of short duration. Insulation deterioration caused by high surge voltages is shown to occur at relatively constant voltages regardless of wave length or polarity. Direct strokes are found to be the cause of principal damage; use of overhead ground wires for apparatus protection is recommended.

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IN A previous paper,[1] the relationships among impulse characteristics of edge gaps, line insulation, and major insulation (that between winding and core and other windings) of a transformer were shown. For example, it was established that the major insulation of transformers had an impulse ratio of approximately 2.2 and that the time lag curve was practically flat down to time lags of 2 μsec. It was also found that coördination with present standards of transformer major insulation was obtained by edge gaps recommended by the transformer subcommittee of the A.I.E.E.[2] There was some question however whether coördination was obtained between transformer major insulation and the standard edge gaps for extremely short time lags which showed a need for further study of insulation and edge gap characteristics for surges of very short duration.

Additional study of this problem has been made. The time lag curves for insulation and edge gaps previously shown are in agreement with the more recent data, which still indicate that coördination is obtained even for surges of very short duration. The ability of transformers to withstand repeated surges is of great interest in connection with the

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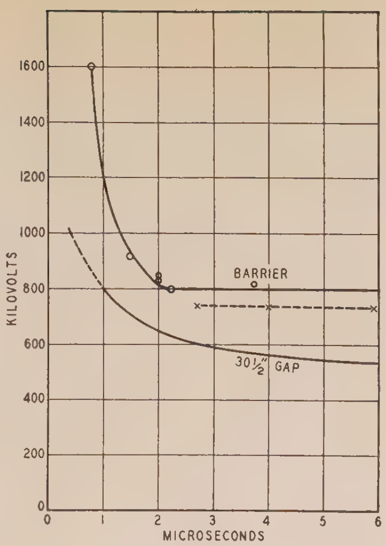
1. For all numbered references, see bibliography at end of paper.

Fig. 1. Results of barrier breakdown tests with single applied surge as compared with results obtained with several surges and with breakdown of coördinating gaps

Points "O" obtained with a single applied surge

Points "X" obtained by applying several surges, starting 10 per cent or more below the breakdown value and increasing in steps up to breakdown. This was the method used in obtaining data presented in the previous paper except at short time lags



The $30^1/_2$-in. gap time-lag values shown indicate the relations that should exist between transformer insulation for a single applied surge and the standard coördinating gap

highest surge voltages. It is well known to all engineers that in testing any material, whether electrically or mechanically, there is found a certain range of values where damage may be done, and where failure may not immediately result. That such damage or deterioration in insulation structures due either to surges or 60-cycle tests might occur is generally believed from previous work, but these opinions as to insulation deterioration from surges are based on puncture tests on small samples not representative of the major insulation of transformers. For these reasons, insulation deterioration due to high surge voltages required investigation. The comprehensive studies here described show that the level at which deterioration can be expected is practically a constant voltage for any one insulation arrangement regardless of wave length or polarity.

The performance of the edge gap at extremely short time lags has been determined and compared with that of the transformer major insulation. Direct strokes are still found to be the source of real danger and overhead ground wires are essential to prevent direct strokes at or near the apparatus. A stroke to the line, however, if several hundred feet away, may be reduced to reasonable limits by the application of suitable protective means.

Conclusions reached as a result of this further study are as follows:

1. Transformer major insulation of conventional types probably is coördinated with the proposed standard coördinating gaps, except that in the case of very high short surges marked deterioration results.

2. Transformer major insulation is shown to have a definite voltage deterioration level, and surge voltages above this level, as permitted by the standard point gaps, definitely result in insulation deterioration.

3. Surge testing as at present recommended by the Transformer Sub-Committee of the A.I.E.E. will not result in any deterioration to the apparatus, providing, of course, the apparatus is properly designed.

4. The best protection that can be afforded to apparatus against damage due to lightning is to provide a protective scheme comprising overhead ground wires, a deion line protector at some suitable distance from the apparatus, lightning arrester at the apparatus, and a ground network.

Insulation Deterioration Indicated by Barrier Tests

While making the surge tests of insulation reported in the previous paper it was noted that the values obtained varied somewhat with the number of tests applied. Accordingly, in obtaining data for the insulation time lag curves, tests were first made in which the insulation was broken down on the first surge applied, this eliminating any effect of insulation deterioration due to repeated tests.

Barriers (similar to Fig. 8 in the previous paper) were made of a similar construction to the major insulation in transformers. Three barriers were tested to determine their maximum 60-cycle, 1 min hold strength. The maximum voltage which these barriers held for 1 min. was 220, 220, and 230 kv or an average of 223 kvrms. The results of the surge test are as shown in Fig. 1. For comparison the time lag curve for a $30^1/_2$-in. edge gap, which would correspond to a 1-min insulation test of 223 kv is shown. It may be noted that these barriers with a 223-kv "hold strength" are not quite equivalent to the major insulation for the 115-kv class even if there were no factor of safety in the one minute test, as the 60-cycle test voltage for this class is 231 kv and the corresponding gap is $31^1/_2$ in.

For further comparison to show the effect of deterioration the results of tests at from 2- to 6 μsec time lag, when several previous tests had been applied, are also shown. It is seen that the insulation and edge gap characteristic curves are closest at

Fig. 2. Typical appearance of barrier after surge breakdown

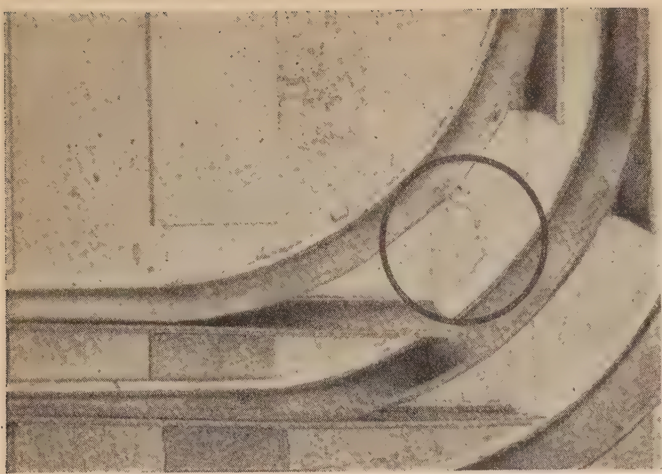


Fig. 3. Typical appearance of deterioration marks from repeated high voltage surges applied to barrier

about 2 μsec. It was the results of such tests as these that led to the adoption of 2 μsec as a critical time lag in the previous study of impulse coördination.

The earlier work in obtaining the shape of the time lag curve indicated that the flat part might be termed the true dielectric strength of the barrier and that the apparent greater dielectric strength shown by the extremely steep rising part of the curve was due to the fact that a certain length of time is required to cause insulation breakdown. It appeared that deterioration results from all voltages above some critical level. Accordingly the deterioration level for impulse voltages for certain barriers, completely representative of transformer major insulation, was fully determined.

The larger barrier (barrier *A*, reported in the previous paper) had an average 1-min 60-cycle hold strength of 345 kv rms. Barriers of this type have been given repeated surge tests using full $1^1/_2 \times$ 40-μsec positive and negative waves. Inspections for evidences of visual deterioration were made and the tests in some instances were continued to failure. The procedure of these tests was to apply at least 100 surges of predetermined value and inspect the barrier at each voltage step up to the point where visual deterioration or marking was first established. The results of the tests are as shown in Table I.

Similarly, tests were made with the same type of barrier (*A*) and with surges chopped by an edge gap after from $2^1/_2$ to 4 μsec. The results of these tests are shown in Table II along with similar tests on a smaller barrier (*B*). The smaller barrier had an average 60-cycle 1-min hold strength of 223 kvrms. These barriers are exactly similar to the ones used in obtaining the data shown in Fig. 1

For very short surges, waves were used that rose at a rate of 1,500 kv per μsec and which were chopped on the front by edge gaps. These tests were made only on barrier *B*. The procedure was to use a given gap setting, apply 100 surges, and then increase the gap setting. Inspection of some of the barriers indicated that marking as in the previous tests was not obtained, but failure was the first indication of deterioration.

Comparison of the results in Tables I and II for full and 2-μsec chopped waves for barrier *A* show that the voltage deterioration level is approximately the same. Table II shows the relationship between the levels of barriers *A* and *B*. Tables II and III show that the deterioration level is the same at both 2 μsec and for very short times. All of this indicates that the deterioration level for barriers representing transformer insulation is the same for full waves, and for waves chopped at from 2 μsec down to approximately 0.4 μsec.

From Tables I and II, tests up to 870 kv on barrier *A* do not cause any visible deterioration. The large number of surges applied above this voltage indicates that even visual marking does not constitute serious damage. As stated before, the maximum 1-min 60-cycle hold strength of barrier *A* was 490 kv crest. This gives a ratio of 870/490 or 1.78. For barrier *B*, this ratio is approximately 565/316 or 1.79, where 316 kv is the maximum 1-min 60-cycle hold strength of barrier *B*.

It should not be inferred from these tests that the ratios and data above apply either to all types and arrangements of barriers, or to all transformers as actually constructed. The ratio may vary over a wide range with different barriers or the arrangement of insulation in different designs. The principle of a constant voltage deterioration level however does apply to all transformers. Where the transformer winding insulation is as strong or stronger than the major insulation, as in a surge proof transformer, and proper design methods and adequate factors of safety are used, impulse tests can be made without fear of deterioration. From these tests it is possible to draw the following conclusions:

1. The strength of these barriers is independent of polarity.

Table I—Results of Repeated Applications of Full $1^1/_2 \times$ 40-μsec Waves

Barrier	Surge Voltages (kv) Held 100 Times Without Marking	Total Number Surges Applied Without Marking	Surge Voltage (kv) at Which Marking Occurred	Number of Surges at Marking Voltage	Total Surges Applied
Barrier A—positive waves					
1	560–615–675–735–790–850–910	700	965	100	800
2	705–760–820–880	400	940	100	500
Average voltage held without marking, 895 kv					
Barrier A—negative waves					
			Surge Voltages (kv) Applied 100 Times After Marking Occurred and Failure Voltage	Number of Surges Above Marking Voltage	
3	720–760–805–850	400	900 945 (failed after 2 shots)	102	502
4	720–760–805–850–900	507	945–990 1030 (failed after 24 shots)	224	731
5	720–760–805–850–900–945	605	990 1030 (failed after 8 shots)	108	713
Average voltage held without marking, 900 kv					

2. Marking and insulation deterioration occurs at a voltage level constant for any given design of barrier from full $1^1/_2 \times 40$-μsec waves down to short chopped waves of 0.4 μsec. With these data, it is reasonable that this same level would hold for still shorter chopped waves.

The above conclusions are based on tests on barriers. To demonstrate that they apply to complete transformer designs, a particular 230-kv design has been tested 100 times with impulse voltages at 1,430 kv. This shows that when the design is made properly and the deterioration limit is not exceeded, deterioration does not accompany impulse testing.

Short Wave Surge Breakdown of Edge Gaps

To view the general coördination problem from a broad and scientific aspect, the breakdown strength of edge gaps was investigated with extremely short surges, of such duration as would be associated with lightning in case there was a direct stroke at the apparatus. Inasmuch as very little, if anything, has hereto been published on the edge gap characteristics for such very short surges, in addition to the test data reported below, there is also described briefly the technique of test as well as the difficulties besetting testing of this kind.

The gaps tested were in agreement with the proposed rules for standard coördinating gaps and furthermore they were located immediately adjacent to the surge generator, as close to it as physically possible. The surge generator was set to a sufficiently high voltage to produce breakdown of the gap on the rising front. As indicated by the oscillograms in Fig. 4 the front rises substantially at a constant rate from 10 per cent to 90 per cent of the crest voltage. The rounding up near the crest is due, partly, to the capacity load produced by the heavy streamer discharge, as breakdown of the gap is in progress; partly, to the combined arc and inductive drop which is maintained across the gap at complete breakdown until the full surge generator current is discharged through the gap; and in some measure, this rounding is partly due to imperfect response, which is inherent even in the best potentiometers available when measuring extremely short voltage-time variations.

It seemed then logical for the special investigation at hand to plot the crest voltage E of the gap breakdown against the time duration T on the rising front, as indicated in oscillogram A (Fig. 4). Accordingly the surge voltage breakdowns of $9^1/_4$ in., $18^3/_4$ in., and other gaps for fronts rising uniformly to crest in times ranging from 1.0 to 0.2 μsec have been

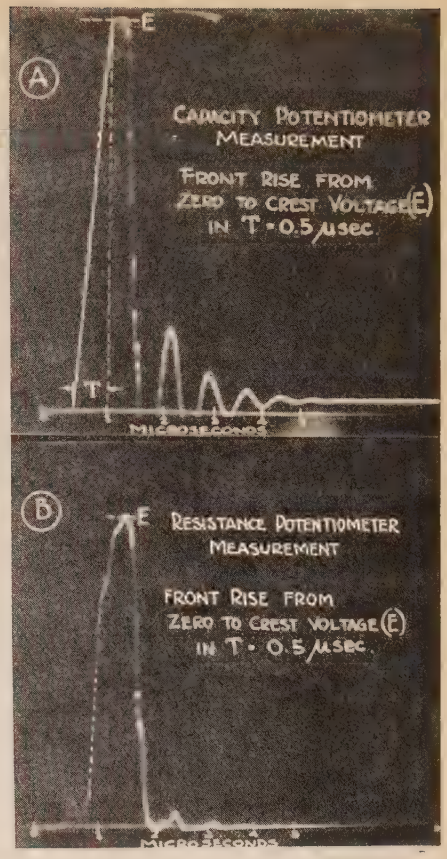


Fig. 4. Oscillograms of point gap flashovers on the fronts of steep waves

Oscillogram A shows the method of analysis of oscillograms to obtain time T to beginning of flashover

Oscillograms A and B show a comparison of similar waves as recorded by the capacity and resistance potentiometer. The rapid response of the capacity potentiometer is indicated by the sharp break in voltage at the beginning of flashover. The flat part at the crest of oscillogram A is due to streamer formation, length of lead, and possibly reactance drop of surge current flow across gap

Table II—Results of Tests With $1^1/_2 \times 40$-μsec Waves Chopped by Point Gap After From $2^1/_2$ to 4 μsec

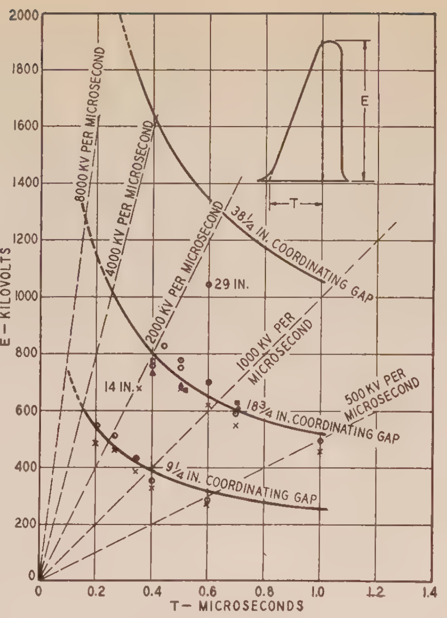
Barrier	Surge Voltages (kv) Held 100 Times Without Marking	Total Number Surges Applied Without Marking	Surge Voltages (kv) Applied 100 Times After Marking Occurred, and Failure Voltage	Number of Surges Above Marking Voltage	Total Surges Applied
Barrier A—positive waves					
1	790–830–865	307	900 940 (failed after 28 impulses)	128	435
2	790–825–865	307	900 940 (failed after 5 impulses)	105	412
Average voltage held without marking, 865 kv					
Barrier A—negative waves					
3	785–825–860	302	910 950 (failed after 25 impulses)	125	427
4	785–820–855	305	890 (failed after 98 impulses)	98	403
5	790–830–860–905	406	940 (failed after 32 impulses)	32	438
Average voltage held without marking, 870 kv					
Barrier B—positive waves					
6	468–510–555	300	610 (failed after 56 shots)	56	356
Barrier B—negative waves					
7	540	100	585	100	200

Table III—Results of Tests Made With Short Chopped* Surges

Barrier	Surge Voltages (kv) Held 100 Times Without Marking	Surge Voltages (kv) at Failure	Gap Length at Failure	Surges Applied Up to Time of Failure
Barrier B—positive waves				
1	470–540–630	675	17″	315
2	540	600	14	143
3	540	600	14	156
Average	570	625		
Barrier B—negative waves				
4	470–540	600	14	300
5	540	600	14	120
6	540 600	650	16	314
Average	560	617		

* The time from the start of the wave to the time of failure was between 0.4 and 0.5 μsec.

Fig. 5. Experimental data for breakdown of coördinating gaps on the fronts of steep waves



⊙ Data taken with capacity potentiometer, positive waves
× Data taken with resistance potentiometer, positive waves
⊡ Data taken with capacity potentiometer, negative waves
△ Data taken with resistance potentiometer, negative waves

Data taken with capacity potentiometer may be slightly high due to length of potentiometer lead; data taken with resistance potentiometer may be low due to slow response. True values should be within these limits where data by both potentiometers are given. Dashed lines show voltages at flashover for different rates of voltage rise or steepness

plotted in Fig. 5. They furthermore may be replotted as a family of curves for constant rates of rises as indicated in Fig. 6. The relationships indicated in Fig. 6 make it appear that extrapolation is fairly safe even over considerable range. One significant finding from these data is the fact that the breakdown strengths to positive and negative waves are substantially the same for all purposes of any importance in this paper.

Following are some of the difficulties and limitations encountered in securing the data in Table III and in Fig. 5:

1. The capacity load permissible was very small. In a case of this kind it cannot exceed the stray capacity of the generator proper if steep wave fronts as indicated are to be obtained with a reasonable size of surge generator. In addition, the surge generator must be designed for and have a voltage rating at least from double to several times the breakdown voltage of the gap on the rising front.

2. To secure reasonably correct measurements of gap or insulation breakdown in the tests made a potentiometer had to be located right at the terminals of the gap or at the electrodes of the insulation. The capacity potentiometer inherently is the type of potentiometer most capable of very rapid response. Unfortunately the capacity potentiometer available during the tests, being fixed in position, would have entailed a part of the discharge circuit drop so that it could not be used directly in these particular tests. A resistance potentiometer accordingly was connected with short potential leads directly across the terminals of the test piece, thus eliminating a voltage drop in part of the surge generator discharge circuit. The resistance of the potentiometer was reduced to the lowest permissible value compatible with its own insulation requirements, in this way securing the best fidelity possible in voltage response even at the very short times. As a further confirmation the resistance potentiometer was checked directly against the capacity potentiometer.

Accounting for the lead drop measured by the capacity potentiometer during the tests, the resistance and capacity potentiometer give substantially the same voltage and wave form, as indicated in both oscillograms of Fig. 4 and also the experimental points on Fig. 5. Briefly stated, although the data on very short waves here presented may not be extremely accurate, all precautions were taken so that it may be considered the best data at present available and amply good for the theoretical and practical purposes proposed in this paper.

The Coördination Problem: Direct Strokes and Short Waves

It is now apparent that there is a definite limit to coördination of transformers with edge gaps. The results show that transformer insulation might be able to withstand exceedingly high short surges, such as might be associated with direct strokes, once or twice, based on the results of Fig. 1. It is equally clear, based on the results of the endurance tests, that injury results, and will lead to eventual failure if such exceedingly high voltage surges are repeated.

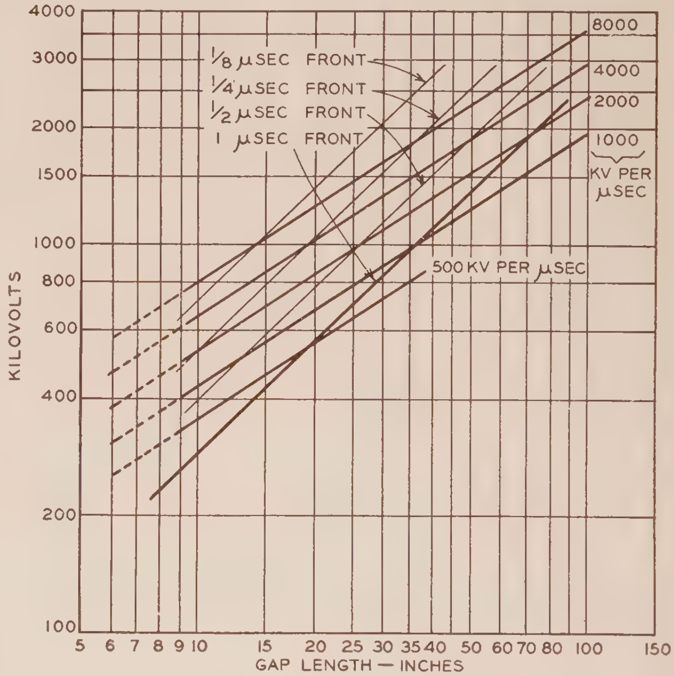


Fig. 6. Breakdown voltages for coördinating gaps on the fronts of steep waves

In high voltage work it often is found that the use of log-log coördinate paper shows interesting relationships and provides means for easy extrapolation. The data for constant rates of voltage rise or steepness and for different values of time to breakdown are plotted. It may be seen that both are pure exponential relationships, are in remarkable agreement with the experimental data, and also appear to determine laws of breakdown which are readily extrapolated

The question of transformer protection against direct strokes then becomes one of economics, in that it may either be decided:

1. To run the risk of failure due to direct strokes;

2. To attempt to so coördinate the transformer insulation that it will withstand direct strokes; or

3. To avoid any possibility of direct strokes at the apparatus.

In many cases undoubtedly the first procedure is

reasonable, as the possibility of a direct stroke may not be great due to the location of the apparatus, and protection other than arresters may be relatively too costly in comparison with the cost of the apparatus or the value of the service. The second procedure is not sound at all if edge gaps are used. The actual steepness of lightning voltages can only be surmised, and even with an estimated rate of rise of 4,000 kv per microsecond, direct strokes would result in such high voltages as to be prohibitive for the lower voltage classes (see Fig. 6). For estimated rates of rise of 8,000 kv or more per microsecond, it is prohibitive for any voltage class. It is evident that the desirable thing to do is to prevent direct strokes to the apparatus in so far as possible, and to provide protection only against traveling surges.

Many have been the suggestions made to limit the abnormally high voltages that would result from a direct stroke at the apparatus. The use of sphere gaps would have certain merits were it not for the clumsiness of this type and of similar types of gaps, the fact that provisions have to be made to protect the spheres from the weather, dirt, etc., and also the need of setting the gap at less than half-diameter spacing in order that it operate at very short time lag without exceeding substantially unity impulse ratio. Limiting devices to fix the voltage to a constant value are no doubt desirable whether these be in the form of sphere gaps, lightning arresters or what not, but full assurance of their characteristics is essential to apply them properly.

Any scheme or method of protection that is to receive consideration must have at least 2 essential requirements:

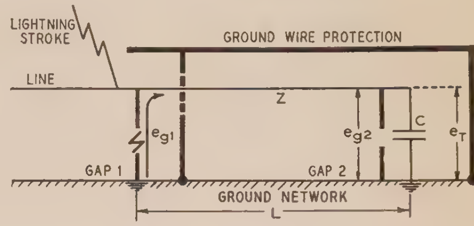
1. Practicability, in the sense that it can readily be incorporated with the normal design of the line and station, an advantage being to apply a method of protection that has already been well established through past developments and practical experience.

2. Economy.

Briefly Fig. 7 illustrates an ideal arrangement which conforms in a good measure with the foregoing 2 requirements. It consists of a ground wire protection covering the substation and extending over the line for several hundred feet, where ground wires are not provided on the entire line. For the stations of higher voltage class, the regular ground wire protection with 2 or more ground wires, ample line insulation, spacing between ground wires and line wires, and low ground impedance (not exceeding a few ohms or where necessary a counterpoise) are found from experience to furnish good shielding.

The substation and apparatus as well as a length of line, L feet, can now be considered well shielded from most direct strokes. This complete shielding is secured according to the modern technique of ground wire protection, low ground resistance at the tower footings, as well as the use of the counterpoise. However, for low voltage circuits, sufficiently low ground resistances at tower footings to obtain ideal conditions are difficult to secure. To overcome this difficulty, the use of diverters has been recommended, but this does not appear to be entirely effective except as a shield from direct strokes to the line in the region of the diverter. However, a direct stroke to the line beyond the diverter would discharge over gap No. 1, still requiring very low ground resistance. Therefore a ground cable system extending from the station parallel to the line and solidly connected successively to the first 2 or more towers and beyond the first gap is here recommended to avoid this difficulty.

Fig. 7. Effective method of protecting apparatus against direct strokes at or near substation



It is beyond the scope of this article to restate the fundamental principles of ground wire protection,[3] so it is immediately assumed that the salient features of shielding against direct strokes have been incorporated as outlined diagrammatically in Fig. 7. Direct strokes to the line at a distance greater than L feet are intercepted and discharged at the coördination gap No. 1. Due to the time-lag phenomena (curves of Fig. 6) a surge voltage e_{g1} is bypassed to the line. This surge travels over the segment of line L and builds up a voltage across the capacity C of the apparatus, which we shall denote as e_T. There are reflections back and forth between the two ends of the line segment L. The following analysis summarizes the traveling wave phenomena and enables readily the computation of e_T from any set of circuit conditions and voltage e_{g1} considered.

The voltage built up across a condenser C connected in series with an infinite line of surge impedance Z, in the case of a unit rectangular wave, is $e_1(t) = 2\left(1 - \epsilon^{-\frac{t}{ZC}}\right)$. Then by superposition, the voltage built up across the condenser C by any voltage (a function of t) $e_{g1}(t)$ (see Fig. 7) is for the first incidence

$$e_{T1} = \int_0^t e_1(t - \lambda)\, e'_{g1}(\lambda)\, d\lambda \tag{1}$$

where $e'_{g1}(\lambda)$ is the derivative of $e_{1_g}(\lambda)$ and is considered to rise from zero to crest and back to zero.

Simply stated, this integration process is nothing more than dividing the incoming voltage wave $e_{1_g}(t)$ into a series of rectangular components, each component producing a resultant voltage at the condenser similar to that of a simple rectangular wave. All these components can then be summed up to obtain the combined effect of all, thus giving the voltage e_{T1} at the condenser. This summing up may be done mathematically, as stated in equation 1, or often more conveniently graphically, as in the case considered later in Fig. 8.

A voltage is then reflected back to gap 1 as indicated below

$$e_R = e_{T1} - e_{1g} \tag{2}$$

This reflected voltage is reversed in polarity (nega-

tive reflection) at the grounded end (gap 1, inasmuch as gap 1 is still discharging) and returns to the terminal apparatus at time $t = \frac{2L}{1{,}000}$ μsec. Much the same as indicated in equations (1) and (2), a second reflection is produced, setting up a voltage e_{T2} across the capacity. Subsequently, third, fourth, and other reflections are produced, but account should be taken in the computation of the fact that rapid attenuation would result, especially in the case of high voltages of very short duration as are here considered. The voltage e_T indicated in Fig. 7 then is the sum total of the first incidence plus effect of the successive reflections, that is

$$e_T = e_{T1} + e_{T2} + \ \ldots \tag{3}$$

In Fig. 8 is illustrated an application of the above relationships to a practical problem, where the voltage e_{g1} by-passed is represented as rising uniformly and chopped instantly to zero at the crest value E. The duration $T = 0.4$ μsec and the parameters for the line and apparatus are $Z = 200$ ohms, $C = 5{,}000$ $\mu\mu$f and $L = 500$ ft. For a 38¼-in. gap and a rising front of 4,000 kv per microsecond the maximum voltage E would be 1,600 kv (curves of Fig. 6) and the maximum voltage, e_T (max) across the apparatus would be limited to approximately 500 kv, which would be a safe value for coördinated apparatus.

Had the length of shielded line been considered as $L = 1{,}000$ ft the second reflection would have occurred at a time $t = 2.5$ μsec instead of approximately 1.5 μsec. It should be noted as a matter of general importance that the length of the line (time $= \frac{2L}{1{,}000}$) relative to the time constant of the line impedance and the apparatus ($t = ZC$) and also taking into consideration the duration of the voltage e_{g1} should be such as to avoid any appreciable adding up of the reflections.

It is well appreciated that due to the lead connect-

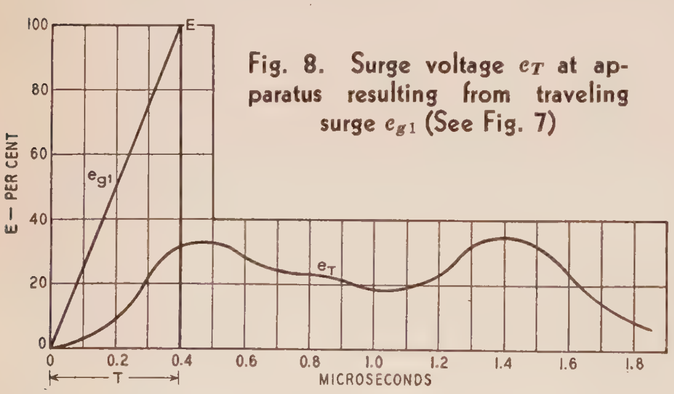


Fig. 8. Surge voltage e_T at apparatus resulting from traveling surge e_{g1} (See Fig. 7)

ing the line to gap 1, the voltage e_{g1} would not drop abruptly at the crest E to zero, but remain flat and decay gradually to zero value in 0.2 μsec or more depending on the height of the tower. The oscillograms in Fig. 4 illustrate clearly the type of wave passed on to the apparatus. This consideration does not change the principle although it would modify the results obtained in Fig. 8.

Unless unusual care is taken to reduce the effective tower footing impedance the voltage e_{g1} instead of reducing to zero value would remain at a value IR for some time, this drop being equal to the product of the lightning stroke discharge current I and the tower footing resistance R. Since the currents are known to reach values of from 100,000 to 150,000 amp it is desirable that the ground resistance be reduced to a very few ohms. In fact the desirable arrangement is to extend several cables in the ground from the station to the first 2 or more adjacent towers. This requirement in the station and apparatus shielding is very essential for the medium and low voltage classes.

This paper does not propose to treat in full detail and in its full ramifications the subject of shielding substations and apparatus from direct strokes. The general problem can readily be analyzed in its full detail following the method of attack outlined above. For a given condition of voltage class, apparatus capacity and line impedance, an economical layout of ground protection can be determined.

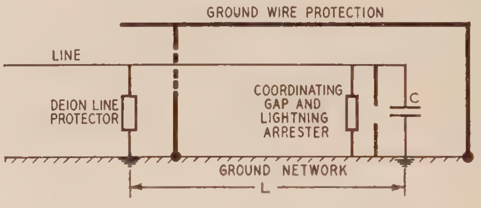


Fig. 9. Suggested method of protecting apparatus and substation against both damage and outage due to direct strokes at or near substation or due to traveling waves

It can be readily seen that with this scheme of protection apparatus may be furnished a substantial measure of protection against direct strokes and high voltage traveling surges. In fact, longer surges, in the order of 1 μsec chopped at gap 2 are much more to be feared. Such conditions may occur from lightning strokes a long distance out on the line and reflecting at the apparatus. In such a case, a voltage limiting device such as the arrester in parallel with gap 2 will provide a considerably increased factor of safety as well as protection against outage. Furthermore, since discharges at gap 1 also may entail service outages, deion line insulator protectors may be used in place of gap 1 as shown in Fig. 9. This arrangement has the merits of eliminating service outages and furnishing a far greater margin of protection than could be obtained with coördinating gaps alone.

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Electronic Regulator for A-C Generators

This paper describes circuits and operating details of an electronic device designed to provide, through field excitation control, a regulation of a-c generator voltage within a range of $\pm 1/10$ per cent.

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IN THE MAJORITY of voltage regulator applications a regulator sensitivity of $\pm$ from $1/2$ per cent to $\pm$ 1 per cent is entirely satisfactory, and the various types of electromagnetic voltage regulators may, therefore, be applied successfully. In applications where very close voltage regulation is needed, electromagnetic type regulators do not prove adequate. Particularly in connection with testing equipment for forced life test for lamps there has been a definite need for faster acting and more sensitive voltage regulators, and to meet this need the type of electronic voltage regulators have been developed as described in this paper.

Operation of these regulators during a period of up to 16 months indicates that electronic type voltage regulators will give a consistent regulation within a range of $\pm 1/10$ of one per cent, and oscillographic tests prove that the speed of response of the electronic type regulators is higher than obtained with the best of the electromagnetic type of regulators.

The performance and reliability of the electronic type voltage regulators have been so satisfactory that it seems safe to predict that during the next few years electronic type voltage regulators will find wide application in the industrial and the central station field. For industrial and central station application the extreme sensitivity of the type *AT* regulator as described in this paper is not needed, and therefore for such applications simplified electronic regulators have been developed. These regulators compare favorably with the vibrating type voltage regulator in respect to sensitivity and speed of response, and due to the simplicity of adjustment and the absence of maintenance, they should appeal strongly to operating engineers.

An electronic voltage regulator recently developed for general industrial applications does need any dry cell battery, is equipped with 2 detector tubes operating in parallel and 2 pairs of grid glow tubes also operating in parallel, and the circuits are so designed that failure of any one tube in the detector circuit or in the power circuit will not cause any change in the regulated voltage.

Full text of a paper recommended for publication by the A.I.E.E. committee on automatic stations, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 26, 1934; released for publication April 16, 1934. *Not published in pamphlet form.*

Regulator Circuit Design

Two slightly different circuits have been used as shown in the schematic diagrams in Fig. 1 and Fig. 2. These circuits are similar except for the voltage indicating tube and the connections to this tube. In the type *AT* regulator shown in Fig. 1 a type *RO-587* full wave rectifier is applied as the voltage indicating element, while with the type *AT-1* regulator shown in Fig. 2, an *RO-585* diode type rectifier tube is applied. While the *RO-587* rectifier tube is a conventional rectifier where the d-c output voltage is proportional to the anode voltage, the *RO-585* rectifier, which has a tungsten filament, operates at an anode voltage exceeding the saturating voltage so that the anode current will be controlled by the filament temperature, and therefore by the filament voltage.

The basic difference between the two voltage indicating schemes is that the *RO-587* detector gives an indication of the average a-c voltage, while the *RO-585* detector indicates the rms value of the a-c voltage. The *RO-587* scheme is slightly superior to the *RO-585* scheme in respect to the response because there is a small amount of thermal lag in the *RO-585* filament, so the *RO-587* scheme should, therefore, be preferred in applications where the generator wave form remains approximately constant with varying load conditions, that is, when the ratio between the average a-c voltage and the rms value of the a-c voltage does not vary more than the required regulator sensitivity. If the generator wave form is changing, as would be the case if a standard 3-phase generator is operating with single phase load, the *RO-585* scheme, which always regulates for the rms value of voltage, should be used.

Referring to Fig. 1 it will be seen that the generator voltage is applied to the No. 1 *RO-587* tube, and the d-c output is filtered and fed to the voltage adjusting potentiometer P_1. The output circuit of potentiome-

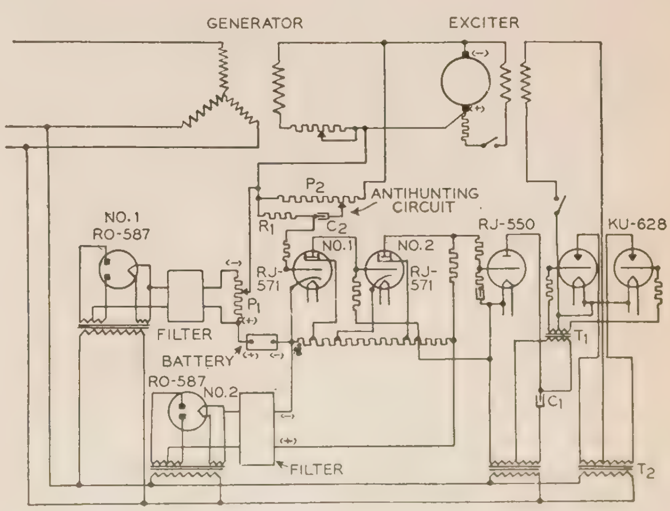


Fig. 1. Schematic diagram of type AT electronic voltage regulator

Fig. 3. Oscillogram showing response of type AT voltage regulator as load is switched on

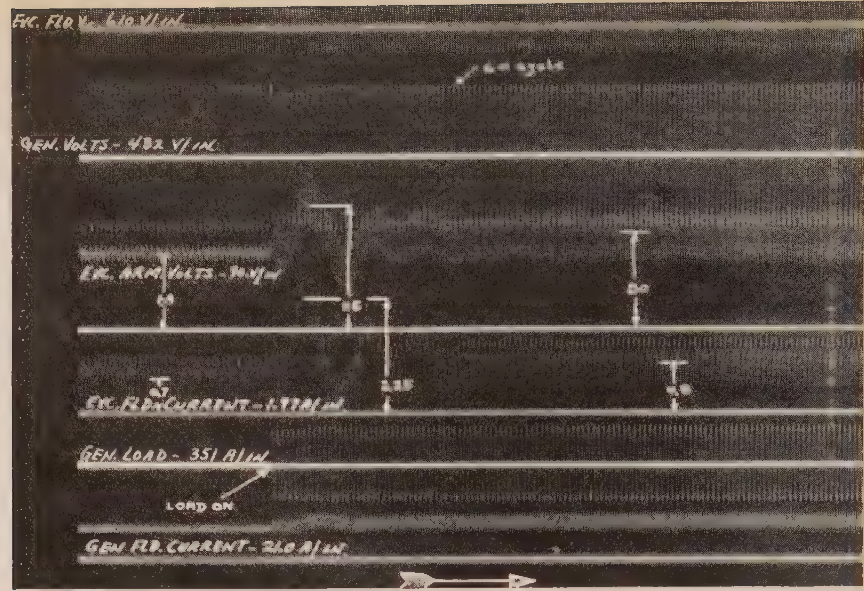
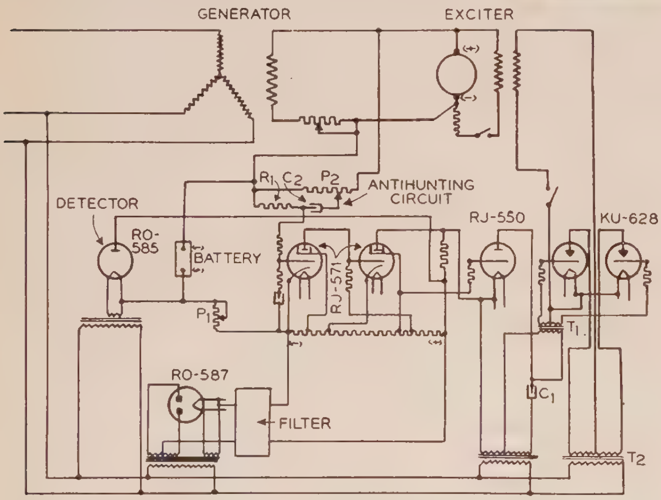


Fig. 2 (below). Schematic diagram of type AT-1 electronic voltage regulator



ter P_1 is bucked against a 90-volt dry cell battery, and the voltage difference is connected in series with the antihunting resistor R_1 between the cathode and the control grid of the No. 1 *RJ-571* screen grid type detector tube so that the No. 1 *RJ-571* control grid voltage is approximately -2 v. By means of the No. 2 *RJ-571* tube the difference between the regulated voltage as indicated by potentiometer P_1 and the battery voltage is amplified, and the output voltage of the No. 2 *RJ-571* tube is applied to control the *RJ-550* tube which functions as a variable phase shift resistor in series with condenser C_1. When the anode current through the *RJ-550* tube is changed, the phase angle position of the primary voltage applied to transformer T_1 is varied relative to the secondary voltage of transformer T_2. By increasing the *RJ-550* anode current the phase angle displacement between the voltage of transformer T_1 and the voltage of transformer T_2 will be decreased from 180 deg leading to approximately 70 deg leading, and this will cause the *KU-628* tubes, which are connected to energize one of the excited field windings, to break down earlier in the cycle, and consequently allow a higher current to flow through the exciter field.

The antihunting action is obtained from the effect of variation in exciter armature voltage acting upon the antihunting circuit consisting of potentiometer P_2, resistor R_1, and condenser C_2. When the exciter armature voltage is constant, the voltage drop across R_1 is zero. If the exciter armature voltage is changing due to the correcting action of the regulator, a charging current will flow into, or a discharging current will flow out of condenser C_2. This current will produce a voltage drop across resistor R_1, with a polarity so as to oppose and diminish the unbalanced voltage conditions in the grid circuit of the No. 1 *RJ-571* tube which caused the corrective action of the regulator.

Assuming that load is applied to the generator with a resulting drop in generator voltage, the No. 1 *RJ-571* grid voltage will become less negative and the current through the *KU-628* tubes, and consequently the exciter field current, will increase, thus tending to bring the generator voltage back to normal. As soon as the exciter armature voltage is increased a voltage drop will appear across resistor R_1, tending to make the No. 1 *RJ-571* grid more negative, and the exciter field current, which at this instant will be considerably higher than prescribed by the new generator load condition, will start to decrease before the regulator voltage is back to normal. This anticipatory action of the antihunting element is imperative in order to obtain stable operation as well as quick response action.

The operation of the antihunting circuit can be clearly visualized from the oscillograms in Fig. 3 and Fig. 4. These oscillograms were obtained with a 50-kva single phase generator, and during the oscillographic tests full load at 0.95 power factor was applied to the generator (Fig. 3), and full load was disconnected from the generator during oscillogram Fig. 4. It may be seen from Fig. 3 that within 5 cycles after the load had been applied to the generator, the exciter field current had increased from 0.7 to 2.35 amp. At this point on the oscillogram the exciter field current starts to decrease due to the action of the antihunting circuit, even though the regulated voltage is still below normal. The

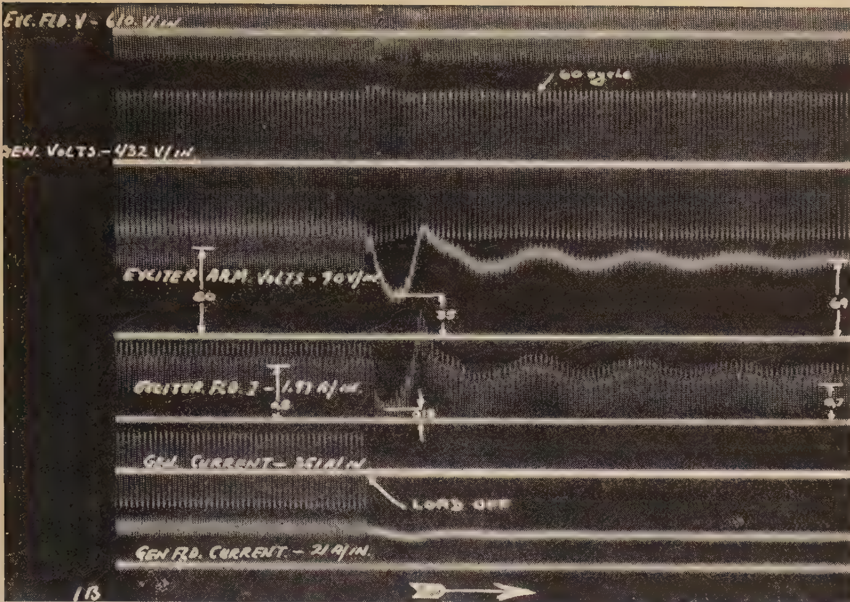
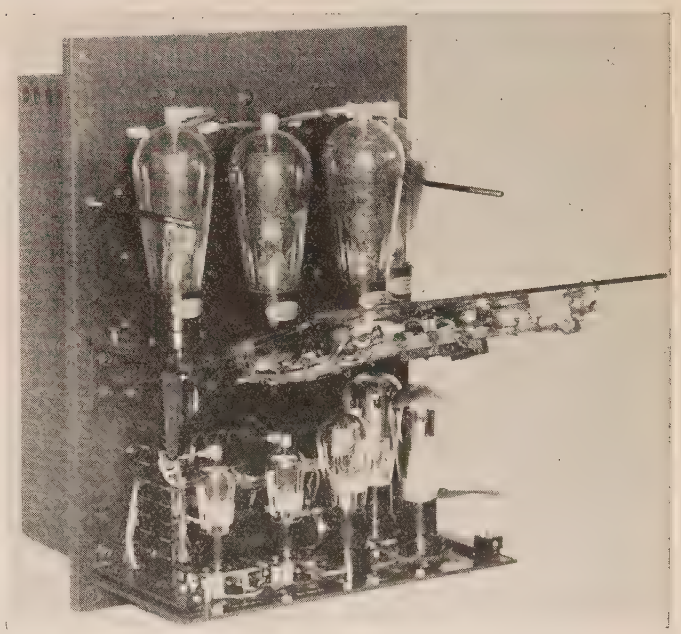


Fig. 4. Oscillograms showing response of type AT voltage regulator as load is switched off

Fig. 5 (below). Type AT voltage regulator with front cover off



quick response characteristic of the electronic regulator is apparent from this oscillogram, and it may be seen that the regulated voltage is back to normal in approximately 10 cycles after full load was applied to the generator.

The *AT-1* electronic regulator shown in Fig. 2 operates on the same general principle as the regulator shown in Fig. 1. When the regulated voltage is increased the current through the *RO-585* tube will increase and the negative bias on the grid of the No. 1 *RJ-571* tube will decrease. Since the cathode-grid connections of the *RJ-550* tube in this circuit is reversed as compared to Fig. 1, the effect of increasing regulated voltage will be a decrease in exciter field current. To obtain the correct polarity of the antihunting resistor, the polarity of the connections between the antihunting potentiometer P_2 and the exciter armature have been reversed as shown in the figure.

Applications of the Regulator

From the photograph in Fig. 5 it may be seen that the electronic regulator is equipped with a total of 4 *KU-628* grid glow tubes, while for the sake of simplicity only 2 *KU-628* tubes were shown in Figs. 1 and 2. In order to use all 4 *KU-628* tubes the exciter field winding should be split into 2 circuits and one field circuit should be connected in series with each pair of *KU-628* tubes, as shown in Fig. 6, which gives the connections for the electronic regulator applied to control the output voltage of synchronous booster equipment. The equipment is started by having one exciter field winding self-excited. When the generator voltage is approximately normal, a-c voltage is applied to the electronic regulator in order to heat up the tube filaments. After approximately one minute switch No. 2 of Fig. 6 may be closed and the exciter field rheostat may be turned in until the *KU-628* tubes assume their share of the exciter field current. Switch No. 1 is now thrown from the self-excited to the separately excited position and all 4 *KU-628* tubes will now be in control. The regulated voltage may then be adjusted by means of potentiometer P_1 shown in Fig. 1 and Fig. 2.

The booster circuit shown in Fig. 6 is of considerable interest due to the difficulties encountered on account of the many variables affecting the regulated voltage in such a circuit. Because quick response regulator action was the predominating regulator requisite in this application, it is doubtful whether any other type of regulator but the electronic regulator could have handled this problem successfully. The booster generator, which had a capacity of 30 kw, was synchronously driven from a 220-volt 60-cycle line, the voltage of which was varying within a range of 10 per cent. Since this equipment was used for life tests of lamps, it was imperative to maintain the regulated voltage, 126 volts, within a range of ±0.1 per cent, when the booster generator load was changing from zero to 2,500 amp and voltage E_L was changing from 114 to 126 volts.

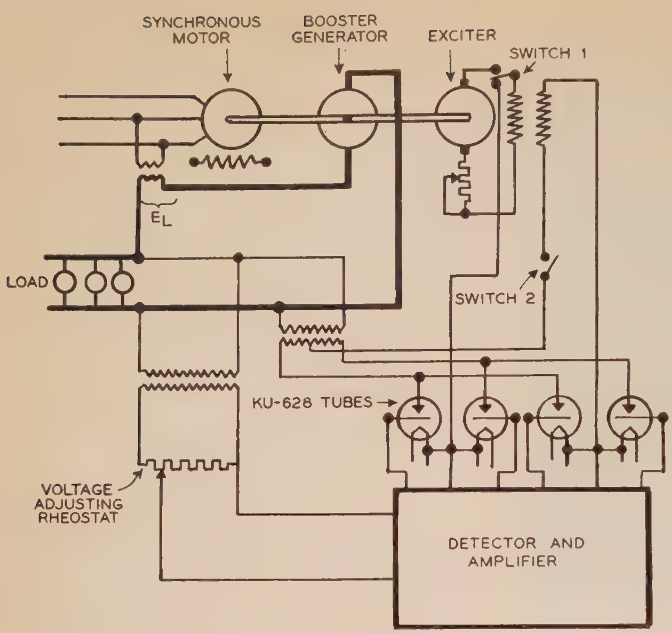


Fig. 6. Schematic diagram of type AT voltage regulator arranged for synchronous booster application

Due to the 25-deg change in the synchronous motor rotor position relative to the line voltage, from no load to full load, and due to a similar change in the phase angle of booster voltage, it was necessary to adjust the position of the booster armature to give a 25-deg leading booster voltage at no load. With full load on the booster, the booster voltage would lag the line voltage by 25 deg. In order to maintain the regulated voltage constant, the regulator had to correct quickly, not only for changes in line voltage and load current, but also for changes in the position of the booster rotor relative to the line voltage.

Notes on Performance

One of the *AT* regulators has been in operation on lamp testing equipment during approximately 16 months and during the period from Nov. 10, 1933, to Dec. 18, 1933, the equipment was in service a total of 34 days. This particular equipment is used for forced voltage lamp testing and is started up every morning at 8:15 with full lamp load, and continues to operate until 4 o'clock in the afternoon when all lamps will be burned out. During this period from 8:15 a.m. to 4:00 p.m. the generator load will be tapering off to zero as the lamps gradually burn out. In the following table is shown a résumé of the voltage readings taken every 15 minutes from 8:15 a.m. to 4:00 p.m. The first column gives the number of days during which the regulator voltage remained within a definite zone during the 8:15 a.m. to 4:00 p.m. period. The second column gives the same data covering the period from 10:00 a.m. to 4:00 p.m. The reason why the second column is better must be ascribed to the time required to bring the regulator up to a constant temperature, after being started up from the cold condition.

Regulated Voltage Range ± Per Cent	Days During Which Regulated Voltage Did Not Exceed Range: 8:40 a.m. to 4:00 p.m.	Days During Which Regulated Voltage Did Not Exceed Range: 10:00 a.m. to 4:00 p.m.
0.05	7	17
0.08	17	24
0.125	21	30
0.2	28	34
0.25	33	
0.33	34	

From the second column of the table may be seen that on 24 out of 34 operating days, the sensitivity of the regulator was ±0.08 per cent or better, during 30 days the sensitivity was ±0.125 per cent or better, and never during the 34 days of operation was the sensitivity less than ±0.2 per cent.

Design of Electronic Type Monitor

In order to eliminate the temperature effect of the type *AT* electronic regulator during the warming up period an electronic type monitor as shown in Fig. 7 has been designed. This equipment is arranged so that the indicating element, which consists of 2 Mazda lamps and 2 resistors, is connected directly to the generator bus without any intermediate transformers which would introduce a temperature error.

When the regulated voltage is normal, the voltage across the grid transformer T_1 connected across the bridge circuit is zero. If the regulated voltage departs from normal there will be a definite voltage across this grid transformer. This voltage will

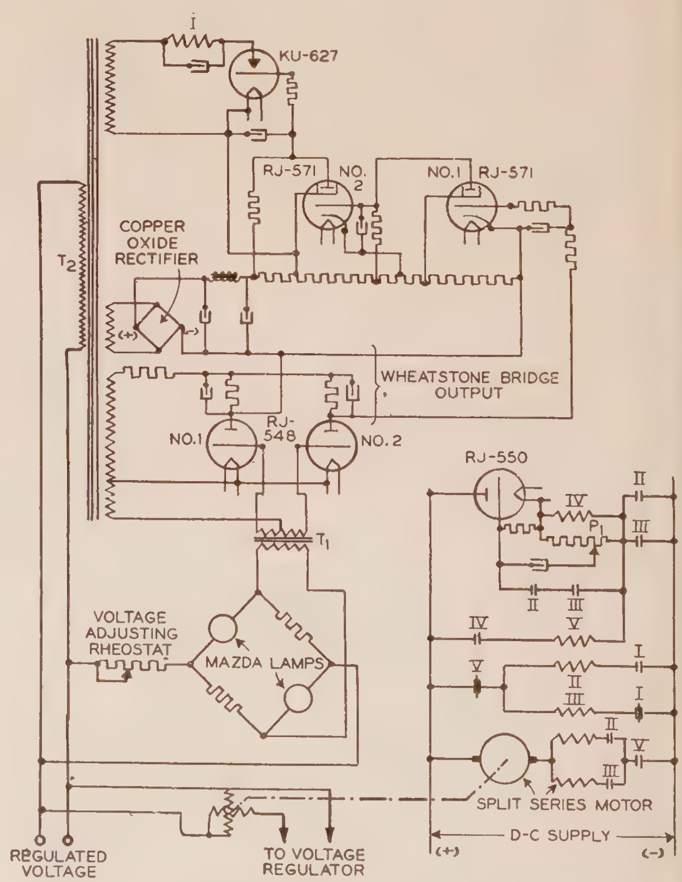


Fig. 7. Schematic diagram of electronic monitor

either be in phase with the regulated voltage or 180 deg out of phase, depending upon whether the regulated voltage is too high or too low. The operation of the voltage balancing bridge is based on the fact that the resistance of a Mazda lamp will increase with increasing lamp voltage, while the resistance of the Ward Leonard tubes connected in series with the lamps is practically independent of the applied voltage. In this connection may be mentioned that special type resistor tubes wound with copper nickel wire were used. This wire has a lower temperature coefficient than the nichrome wire used with the standard type resistor tubes.

The secondary winding of the grid transformer is connected to control a pair of *RJ-548* amplifier tubes energized from the main transformer, T_2, so that the current through the No. 2 *RJ-548* tube will increase and the current through the No. 1 *RJ-548* tube will decrease if the regulated voltage is increased. The 2 *RJ-548* tubes in combination with their anode resistors are connected in a wheatstone bridge circuit and the output of this bridge is applied in the grid circuit of the No. 1 *RJ-571* amplifier tube, which through the No. 2 *RJ-571* amplifier tube controls the *KU-627* tube which is connected in series with relay No. 1.

For an increase in regulated voltage the operation of the equipment is therefore as follows: The current through No. 2 *RJ-548* is increased. This causes an increased negative bias on the control grid of the No. 1 *RJ-571* tube, and the anode current of the No. 1 *RJ-571* tube will decrease. Decreasing No. 1 *RJ-571* anode current will decrease the negative bias

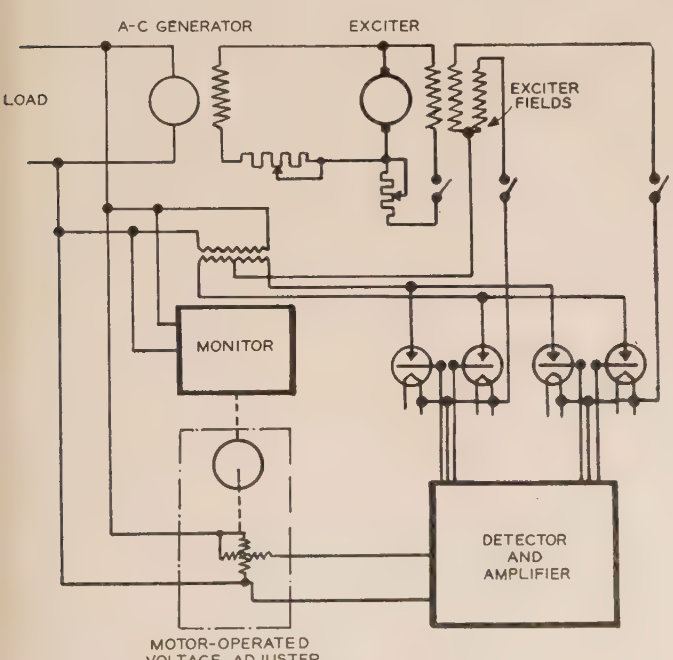
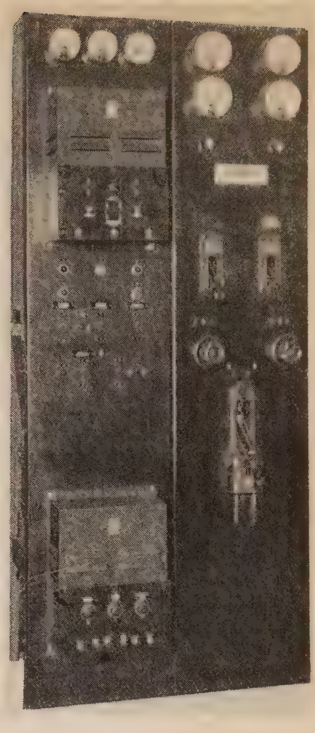


Fig. 8. Schematic diagram of type AT regulator with monitor

on the control grid of the No. 2 *RJ-571* tube which will produce an increase in the No. 2 *RJ-571* anode current with a consequent increase in the negative bias on the grid of the *KU-627* so that the current flow through the *KU-627* will be stopped and the No. 1 relay deënergized.

Fig. 9. Switchboard with equipment shown in Fig. 8



If the regulated voltage is decreased, the opposite conditions obtain, and the *KU-627* tube will break down and energize relay No. 1.

When the voltage is normal, relay No. 1 will alternately close and open, and will energize either relay II or relay III, but no further relay action will take place. If, however, the regulated voltage remains too low or too high during a definite time interval of from 1 to 24 sec, dependent upon the adjustment of potentiometer P_1, relay IV will be energized. Supposing the voltage is too high, relay I would be deenergized and relay III energized. "Make" contacts of relay III now energize the time delay circuit, consisting of the *RJ-550* amplifier tube, relay IV, potentiometer P_1 and the condenser discharge circuit, and also close the control circuit for the motor operating the voltage adjuster which is connected to recalibrate the *AT* regulator as shown in Fig. 8. After a definite time interval, dependent upon the adjustment of potentiometer P_1, the current through the *RJ-550* tube is high enough to energize relay IV. "Make" contacts of relay IV energize relay V which completes the motor control circuit and the voltage adjusting motor will start to operate to increase the voltage applied to the detector terminals of the *AT* regulator, and thus decrease the regulated voltage. When relay V operates, "break" contacts of relay V deënergize relay III; but, being a slow releasing type relay, relay III will remain closed during an interval of from approximately $^1/_2$ to 1 sec. When relay III opens, the motor circuit is interrupted and the voltage adjusting motor stops. If the regulated voltage still is too high the sequence of relay operation will be repeated, and the motor will continue to operate during a period of from $^1/_2$ to 1 sec with intervals dependent upon the adjustment of the time delay potentiometer P_1.

Flashover Voltages of Insulators and Gaps

In an effort to clarify the confusion that has existed during past years regarding the flashover strength of insulators, the A.I.E.E. lightning and insulator subcommittee* has been engaged, jointly with high voltage laboratories of several insulator manufacturers, in an investigation to determine and eliminate differences in insulator flashover data from different sources, and to obtain reliable flashover data for standard insulators and gaps. In this latest report, the subcommittee presents average 60-cycle and impulse flashover voltages for suspension insulator strings consisting of 10-in. units with $5^3/_4$-in. spacing, and for coördinating gaps with various spacings.

IT IS WELL KNOWN that a knowledge of the safe dielectric strength of insulation and the relative flashover characteristics of line and station insulators, bushings, and air gaps is essential to a coördinated design of an electric power system if it is to be free from major interruptions. A realization of the importance of this coördinated design (largely a problem of determining the insulation strength of porcelain insulators where the dielectric breakdown is in air) may be gathered by referring to some of the work already done on the problem (see bibliography at end of paper).

The situation confronting the station and line designer until some 5 years ago was a complete lack of reliable flashover data on insulators, actual values given by manufacturers on what were, or appeared to be, similar insulators differing by as much as 25 to 30 per cent for 60-cycle flashovers and some 60 per cent for impulse flashovers. This condition, as well as the general principles of insulation coördination, were pointed out as early as 1928[1]; and shortly thereafter the problem of insulator flashover strengths and characteristics was given intensive study and investigation.

In the early work of the lightning and insulator subcommittee, it was realized that impulse data must be made available on a basis both comparative and representative of natural lightning conditions that might be expected in the field. Intensive field investigations on natural lightning that were in progress in 1927 were supplemented in 1929 by the subcommittee's efforts to clarify the rather confused situation in the data then available on the flashover strengths of insulators. The first step was the establishing of preferred impulse test waves or yardstocks of measurements, the latest recommendations on which are covered by a subcommittee report published in 1933.[17] The situation in the field of 60-cycle flashover voltages of insulators, while less confused than the impulse voltages, presented a problem that also required attention.

Through the efforts of the subcommittee members associated with company laboratories where flashover tests of insulators were made, slow but sure progress so far has been made in reaching generally agreed upon flashover voltages of suspension insulators and one form of air gap. The carrying on of this work in the laboratory has been stimulated by other agencies. The transformer subcommittee of the A.I.E.E. committee on electrical machinery, as well as the National Electrical Manufacturers' Association and the Edison Electric Institute, through their committees on insulation coördination, have contributed their support to this work.

Results of this work have brought about a much clearer understanding of insulator flashover characteristics and the factors affecting them, so that at present there is reasonably close agreement among the various laboratories on 60-cycle and some impulse flashover voltages of certain commonly used insulators and coördinating gaps (so-called). It is the purpose of this paper to point out in a general way the reasons for past discrepancies in insulator flashover data and the general methods that have been used to eliminate these differences, and to record the flashover characteristics of standard suspension insulators and coördinating gaps that have been proposed for certain uses in the past few years.

Progress in Insulator Flashover Testing

A study and laboratory investigation of the insulator flashover problem showed that the discrepancies in the 60-cycle test data were due mainly to 3 factors:

1. Moisture content of the air (humidity).
2. Measuring instruments (spheres or needle gaps).
3. Sphere gap calibration.

In impulse flashover data the disagreement, which in most cases was great, was due to 7 factors:

1. Use of different test waves and of different definitions for a designated wave.
2. Failure to designate flashover as front, crest, or tail of wave flashover.
3. Failure to observe polarity (positive or negative) effect of test wave.
4. Presence of oscillations in the test wave.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 13, 1934; released for publication April 16, 1934. *Not published in pamphlet form.*

1. See bibliography at end of paper for all numbered references.

* **Personnel of lightning and insulator subcommittee of A.I.E.E. committee on power tramsmission and distribution:** Philip Sporn, *chairman;* I. W. Gross, *secretary;* C. L. Fortescue, K. A. Hawley, J. Allen Johnson, W. W. Lewis, J. T. Lusignan, and F. W. Packer.

5. Inaccuracies in measuring test voltages.

6. Questionable reproduction of the actual applied voltage wave due to different types of potentiometers, and oscillations in the test circuit.

7. Air conditions (air density and humidity).

In the attempt to reach a satisfactory solution of this problem, 4 of the major laboratories of etectrical manufacturers which were best equipped to make 60-cycle and impulse tests (General Electric Company, Westinghouse Electric and Manufacturing Company, Ohio Brass Company, and Locke Insulator Company) coöperated in a study of insulator and gap flashover. To show how carefully the work was conducted during its early stages, a given string of insulators was sent in turn to each of the 4 laboratories for test, and on the basis of the results obtained alterations in test conditions or equipment were made to eliminate such variables as were found or suspected. In this way most of the factors affecting the discrepancies were discovered and eliminated, and a means of reducing test data to a common basis was established.

Progress in the investigation of the causes of past discrepancies in suspension insulators flashover data has been so great in the past 2 years that the prominent laboratories are now in close agreement and are in a position to check these agreed upon values within close limits on standard suspension insulators with their regular test equipment. Correction factors for both 60-cycle and impulse voltages have been determined for certain types of insulators, and are applied to reduce test data to a common basis of humidity; this has eliminated one of the most troublesome factors in the past. Test circuits have been calculated and checked, and measuring spheres and methods have been cross checked.

The coördinating of test results between laboratories, which has been confined almost wholly to suspension insulators and gaps, to 60-cycle dry flashovers, and to positive impulse waves, is expected to be extended gradually to other types of insulators, such as pin and switch insulators and bushings, and to 60-cycle wet flashover data, impulse waves of negative polarity, and various voltage-time characteristics. Now that the ground work for the basic test data has been laid, it is expected that progress in securing these much needed data will be more rapid.

Basis of Present Data

As an outgrowth of the coöperative work of the 4 major laboratories mentioned, the basis to which the flashover data were referred, or corrected, was as follows:

Temperature . . . . 25 deg C.
Barometric pressure . . . . 760 mm of mercury.
Humidity . . . . 6.5 grains of water per cubic foot, corresponding to a vapor pressure of 0.6085 in. of mercury.

Voltage measurements were made with the sphere gap as a primary standard, although the transformer voltmeter coil sometimes was used in 60-cycle testing and calibrated voltage dividers in impulse testing. In the use of the sphere gap, some discrepancies appeared where the calibration of different sized spheres overlapped, and also where sphere sizes and spacings exceeded those given in A.I.E.E. Standards No. 4. Since these sphere gap deviations, within the voltage range covered by standards No. 4, showed relatively small voltage variations they have been ignored mostly in the results presented herein. In the higher voltage range it is planned later to investigate the field of sphere gap calibration further, the values in this higher range given here being the best agreement possible at the present time.

As regards the accuracy of test results given for impulse flashover voltages, it is believed they can be relied upon within approximately plus or minus 5 per cent. The data on insulators were obtained from laboratory tests, each laboratory presenting its average curve of flashover voltages; the average curves of the 4 laboratories then were averaged and this one curve taken as the agreed upon set of values for the insulators tested. By this method, it was found that the spread of the average curves for insulators was not in excess of 5 per cent total, thus bringing any laboratory's curve within about plus or minus $2^1/_2$ per cent of the average curve. Although the agreement between laboratories is quite close on these average flashover voltages, single tests on a given insulator string may deviate from the given data in the order of $7^1/_2$ per cent.

In the case of 60-cycle flashover voltages, it might be expected that the problem of tracing the causes of discrepancies and reaching an agreement could be solved much more easily than with the impulse tests. While this may be the case, impulse tests, because of their importance in insulation coördination, have been given precedence in the investiga-

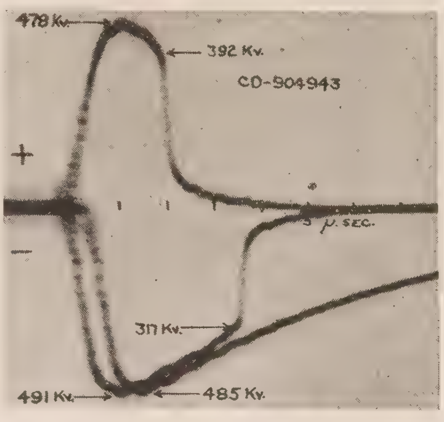


Fig. 1. Cathode ray oscillogram of flashover test on an insulator string consisting of 4 10-in. disk units spaced $5^3/_4$ in., with a 1 x 5-μsec wave

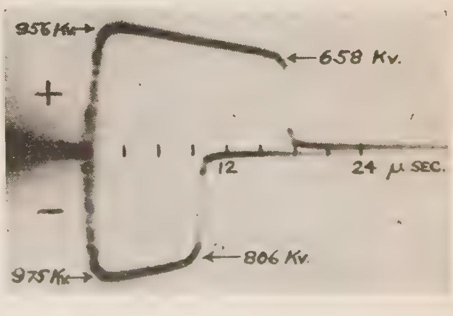


Fig. 2. Cathode ray oscillogram of flashover test on an insulator string consisting of 8 10-in. disk units spaced $5^3/_4$ in., with a $1^1/_2$ x 40-μsec wave

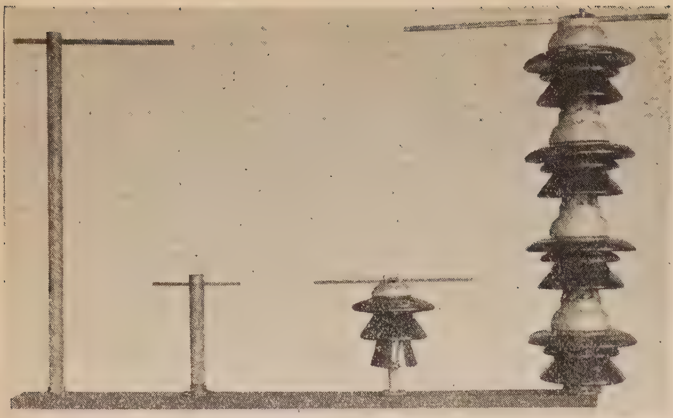


Fig. 3. Coördinating gap of the type used in obtaining the data given in this paper

The large gap is rated 138 kv and its spacing is 38¼ in.; the small gap is rated 46 kv and its spacing is 12¼ in.

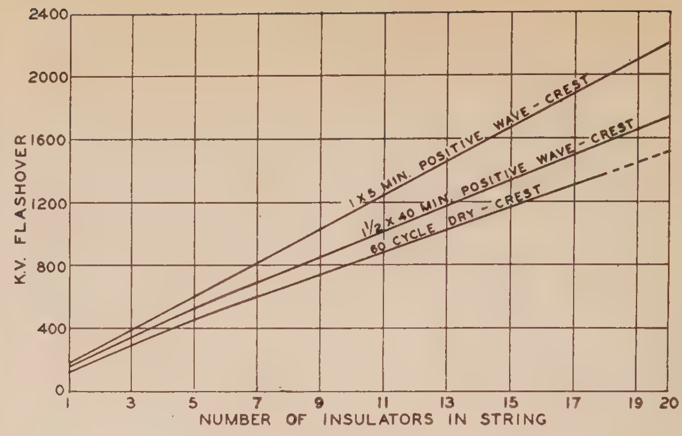


Fig. 4. Flashover voltages of suspension insulator strings consisting of 10-in. units spaced 5¼ in.

Humidity, 6.5 grains per cubic foot; barometric pressure, 760 mm.; temperature 25 deg C

tion work; as a result, there is closer agreement today between various laboratories on impulse test data of suspension insulators and gaps than on 60-cycle test data. The 60-cycle data given herein were obtained from the individual laboratories and, although not as yet definitely agreed upon, are the best representative average data available. The 60-cycle flashover situation, however, is being studied and it is expected that closer agreement soon will result. At the present time many of the average 60-cycle flashover voltages of insulators and gaps are already within the plus or minus 5 per cent mentioned for impulse tests, although some of the 60-cycle voltages may have a tolerance in the order of plus or minus 10 per cent.

While the general procedure in making 60-cycle flashover tests is well understood, the situation is vastly different in impulse testing. Because of the various methods used in the past in making impulse tests and reporting the data, a brief explanation of the methods used in securing the data presented in this paper will be given.

Test waves used were the preferred test waves recommended by this committee,[17] namely, 1×5 and $1^1/_2$×40-μsec waves. The first number in the wave designation represents the time in microseconds from the origin of the wave to the crest, and the second number the time from origin to half the crest voltage on the tail. The minimum impulse flashover voltage recorded is the crest value of the lowest magnitude wave of the specified type that will cause flashover. With this method of testing, flashover of the test specimen invariably takes place on the tail of the wave. Typical test oscillograms are shown in Figs. 1 and 2.

In Fig. 1, which depicts a test on an insulator string consisting of 4 10-in. disk units spaced $5^3/_4$ in. with a 1×5-μsec wave, flashover is shown taking place in 2 μsec on the positive wave and in $3^1/_2$ μsec on the negative wave. The "minimum voltage flashovers" are 478 kv and 491 kv, respectively, although the actual voltages at the instants of flashover were 392 kv and 317 kv, respectively. The full negative wave to which the insulator string was subjected without flashover, as shown below the zero line, had a crest value of 485 kv. Similar tests on an 8-unit string where the $1^1/_2$×40-μsec wave was used are shown in Fig. 2. All impulse test voltages given in this paper are "minimum impulse" test values as just described, and, as before noted, of positive polarity only.

The coördinating gaps on which flashover data are given here were constructed according to the A.I.E.E. transformer subcommittee's recommendations, the general details of the gaps being given in past A.I.E.E. papers.[3,18] Figure 3 shows a photograph of typical 46-kv and 138-kv gaps such as used in securing these data in the laboratory. In making tests, however, only one gap was present at a time, although both gaps are here shown on a common base.

Table I—Flashover Characteristics of Suspension Insulator Strings Consisting of 10-In. Units With $5^3/_4$-In. Spacing

Barometer 760 mm; temperature 25 deg C; humidity 6.5 grains per cubic foot; vapor pressure 0.6085 in. of mercury

Number of Units in String	Flashover Kv (to nearest 5 kv): 60-Cycle Crest, Dry†	Minimum Positive Impulse Waves: 1×5-μsec	$1^1/_2$×40-μsec
1	110*	170**	160**
2	205*	285**	255**
3	300	390	355
4	370	500	440
5	455	610	525
6	525	715	620
7	605	820	695
8	685	930	780
9	760	1,040	860
10	820	1,145	945
11	895	1,250	1,025
12	960	1,355	1,105
13	1,035	1,460	1,185
14	1,105	1,565	1,265
15	1,175	1,670	1,345
16	1,240	1,775	1,425
17	1,305	1,880	1,505
18	1,370	1,985	1,585
19	1,435*	2,090	1,665
20	1,490*	2,200	1,745

* Average values from 3 laboratories.
** Actual values reported by one laboratory only—subject to revision.
† Average values; not definitely agreed upon.

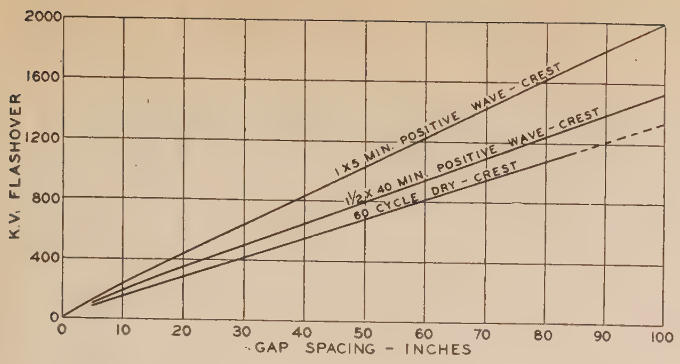


Fig. 5 (Left). Flashover voltages of coördinating gaps

Humidity, 6.5 grains per cubic foot; barometric pressure, 760 mm.; temperature 25 deg C

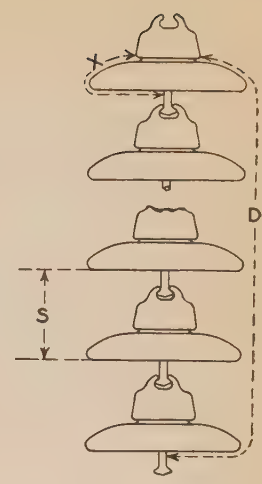


Fig. 6 (Right). Diagrammatic sketch of insulator string

Test Data

The flashover voltages of $5^3/_4$-in. spaced 10-in. disk insulators are given in Table I for insulator strings containing up to 20 units. These data, which have been given in tabular form to eliminate inaccuracies in reading the values from a curve, have been plotted in curve form in Fig. 4 for comparison. Similar data for coördinating gaps are given in Table II and plotted for comparison in Fig. 5 for gap spacings up to 100 in.

As stated before all these values in Tables I and II have been corrected to standard conditions of humidity, temperature, and barometric pressure. They represent flashover voltages that (except as noted) are the averages of results obtained in 4 different recognized laboratories which coöperatively have checked these data. It should be possible in any one of these laboratories to check these given data, at any time with an error not exceeding approximately 5 per cent.

In addition to the 10-in. disk suspension insulator unit with $5^3/_4$-in. spacing, there are in use today many similar units having $4^3/_4$, 5, and $5^1/_8$-in. spacing on which accurate and generally accepted flashover data are not available. The extent of the work necessary by the laboratories and coördinating groups to obtain the data for the $5^3/_4$-in. spaced units and the gaps presented in this paper has made it impossible, so far, to obtain and correlate data on the shorter spaced units. To apply the data for the $5^3/_4$-in. spaced units to shorter spaced units, the following procedure is suggested:

Referring to Fig. 6 which represents any standard insulator string having 10-in. diameter disks, let:

N = Number of insulators in the string.
D = Tight string distance between top and bottom hardware on insulator string.
X = Tight string distance of one insulator unit.
S = Spacing of one unit.
E = Flashover of N units, kilovolts.

Let N_o, D_o, X_o, S_o, E_o be corresponding references to any other similar insulator string having 10-in. diameter disks.

Then, $E_o = E\left(\dfrac{S_o\,(N_o - 1) + X_o}{S\,(N - 1) + X}\right)$

This relation should hold very closely both for 60-cycle and long wave impulse voltages *provided D and D_o are roughly equal,* since it is based on the total length of the breakdown path between approximately equal and similar electrodes (cap of one insulator to the pin of the same or another insulator). For short-tail impulse waves, the results to be expected by this method of converting impulse flashovers from insulators of one spacing to another are not so accurate, the error reported in one case being in the order of 10 per cent. It is believed, however, that the indicated method of conversion of impulse flashover voltages will be of value until actual test data on the insulator units with various spacings are obtained.

Summary

1. The confused situation, which was recognized as existing some 5 years ago and previously, in the matter of flashover voltages of insulators has been investigated during the past few years; the

Table II—Flashover Characteristics of Rod Gaps*

Barometer 760 mm; temperature 25 deg C; humidity 6.5 grains per cubic foot; vapor pressure 0.6085 in. of mercury

Gap Spacing, Inches**	Flashover Kv (to nearest 5 Kv above 150) 60-Cycle Crest, Dry†	Minimum Positive Impulse Waves 1×5-μsec	1½×40-μsec
0.5		24	24
1.0		42	42
1.5		53	53
2.0	42	61	61
2.5		67	67
3.0		75	74
3.5		85	82
4.0	78	95	89
4.5		107	98
5.0	84	120	106
6.0	103	148	124
8.0	119	195	160
10.0	145	240	190
15	215		
20	275	440	350
25	345		
30	415	640	505
35	485		
40	550	835	650
45	620		
50	685	1,035	800
55	755		
60	820	1,230	945
65	890		
70	955	1,425	1,095
75	1,010		
80	1,080	1,620	1,240
85	1,130		
90	1,190	1,815	1,385
100	1,315	2,010	1,530

* Rod gaps as referred to in the paper.
** All voltage values for gap spacings of 15 in. and less subject to revision as most of data in this range are from one laboratory only.
† Average values; not definitely agreed upon.

reasons for many of the past discrepancies have been found and steps have been taken to eliminate them.

2. Whole-hearted coöperation on the part of all groups working on this problem, particularly the laboratories of the 4 electrical manufacturers mentioned, has resulted in an agreement on the impulse flashover voltages of standard insulator strings and coördinating gaps which appear to be accurate within plus or minus 5 per cent. The 60-cycle dry flashover voltages for the same insulators and gaps, although not yet officially agreed upon by the 4 laboratories, are believed to be accurate in most cases within plus or minus 5 per cent, with some values indicating discrepancies in the order of plus or minus 10 per cent. These data are given in this paper.

3. A method of converting these agreed upon data on insulators having $5^3/_4$-in. spacing for use on similar insulator strings having other similar unit spacing, such as $4^3/_4$, 5, and $5^1/_8$ in., is given.

4. The meaning of "minimum impulse" flashover voltage of insulators and gaps is explained, and typical actual oscillograms of 1×5 and $1^1/_2 \times 40$-μsec impulse voltages applied to insulator strings are given.

5. Much more data on the impulse characteristics of insulators and insulation are required than the "minimum impulse" flashover data for 2 different test waves as given in this paper.

6. The groundwork that now has been laid for obtaining impulse data on a common basis, and with comparable results, should result in much more progress in obtaining impulse characteristics of insulators and other insulation which are essential to an intelligent application of insulation coördination.

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Load Totalizing in the New York Area

A remote metering system operating over telephone lines to bring load indications directly to the office of the system operator from important stations in the metropolitan area is described in this paper. A high degree of accuracy has been achieved, and important operating economies are expected.

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In supervising the electric system in New York, the system operator is principally responsible for having in service at all times sufficient generating, transmitting, and transforming equipment to meet adequately any demands that may be made upon the system. In addition, it is the function of the system operator to subdivide the load among the various generating stations in such a manner that the maximum operating efficiency will be maintained. In order to carry out these duties, the system operator must check continually the amount of load carried by each base load station, and be informed promptly of load changes in the regulating station and important tie lines.

In the past, the information was telephoned to the system operator but recent developments in the art of metering have made it possible to use ordinary telephone channels for the transmission of the metered quantities over considerable distances. On Jan. 19, 1934, indicators and recorders to show the loads carried by the principal generating stations were installed in the system operator's office of the New York Edison Company.

Transmission of Load Indications

The generating stations from which loads are transmitted to the system operator's office are shown on the map (Fig. 1). The system operator's office is located at 41st Street and 1st Avenue. The leased telephone lines over which the 2 indications are transmitted are shown in heavy lines. The load transmitted over the Niagara-Hudson interconnection is metered at Millwood and is trans-

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mitted directly to the system operator's office, as shown on the map.

On Fig. 2 is shown the system operator's board with the 10 load indicators arranged across the top. These meters indicate the 25-cycle load at Hell Gate, Waterside, and East River, the 60-cycle load at Hell Gate and Hudson Avenue and the load carried on the Niagara-Hudson interconnection. In addition, the total 25-cycle load and the total 60-cycle load are indicated separately, these 2 indications being combined on another indicator to show the total system generation. This total is again combined with the Niagara-Hudson interconnection load to give on the remaining indicator the total power consumed on the New York system. The last 3 indications, namely, the Niagara-Hudson interconnection, the total system generation, and the total system consumption, are recorded on 3 instruments mounted in a separate panel at the rear of the room, shown on Fig. 3.

At each generating station a polyphase thermal converter is connected to potential and current transformers of each generating unit. The converter develops a d-c voltage directly proportional to the a-c power output of the generator. By connecting the d-c terminals of the thermal converters in series as shown in the diagram, Fig. 5, the total voltage developed is proportional to the total power output of the station. This voltage is impressed on 2 wires (a telephone pair) connecting the terminals of the converters in series with a load indicator in the system operator's office, as shown.

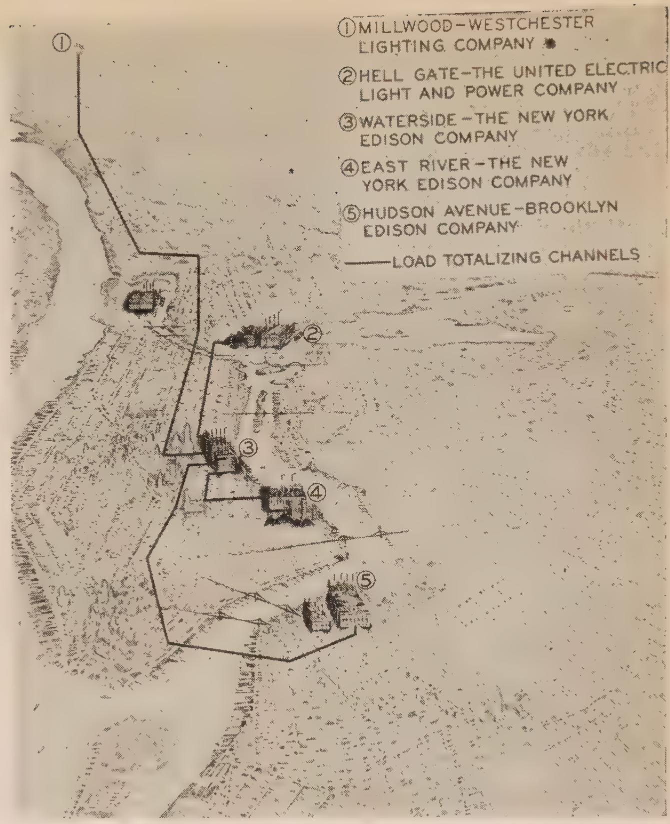

Fig. 1. Map showing locations of generating stations, system operator's office, and telemetering channels

Conversion

The calibration is not affected by normal ambient temperature changes as the temperature of the 2 thermocouple junctions which are located near each other are changed equally, and the difference in temperature, which is the measure of the power, is unchanged. The operating principle of the thermal converter is well known. (A detailed description may be found in P. M. Lincoln's paper, "Totalizing of Electric System Loads," A.I.E.E. Jl., v. 48, Feb. 1929, p. 129.)

Each station load indicator on the system operator's board is equipped with a circuit for transmitting an a-c voltage proportional to the indicated load. The transmitters of the 3 indicators for the 25-cycle stations are connected in series with an indicator showing the total load of these stations. The transmitters of the 2 indicators for the 60-cycle stations are also connected in series with an indicator totalizing their loads. Similarly the transmitters of these 2 totalizing indicators are connected in series with an indicator showing the total system generated load. A transmitter associated with this indicator operates a recorder in the rear of the office.

Thermal converters at Millwood transmit directly to the recorder at system operator's office. A re-

Fig. 2. System operator's board; note the 10 load indicators arranged across top

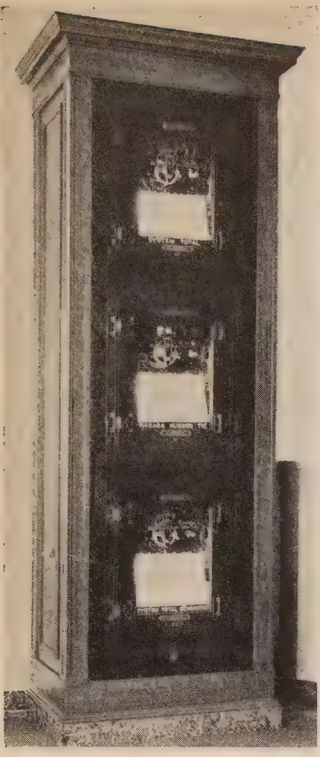

Fig. 3. Load totalizing recorders in system operator's office

transmitter operates the indicator on the board. This is also equipped with a retransmitter which acts in conjunction with that of the system generated load recorder to actuate a system total indicator and recorder. The tie line load is added or subtracted in the system total according to the direction of power flow to or from the system generated load; thus the total loads both generated and purchased or sold are recorded and indicated.

The receiving indicators developed for this installation are shown in Fig. 4. These indicators are of the potentiometer type and convert directly the totalized d-c voltage from the thermal converters into terms of megawatts load.

The potentiometer principle of balancing a known standardized emf against the emf of the converters is used and this permits a high degree of accuracy. Due to the fact that this principle involves balancing voltage and not measuring current, the IR drop in the line does not affect the accuracy. The current flowing is only that which causes the galvanometer to deflect when the voltages are not equal; hence, line resistance or changes in line resistance can affect only the sensitivity. The emf produced by the thermal converter provides ample sensitivity for any of the telephone channels used.

The load indicator is also arranged to transmit a low potential a-c proportional to the load which it indicates. The combining of the various loads as

Table I—Resistance of Telephone Channels

	Ohms
East River	463
Hell Gate	1025
Hudson Avenue	1023
Millwood	3233

shown on Fig. 5 is, therefore, readily accomplished. The retransmitting and totalizing of the incoming load indications has been simplified in this installation by the use of alternating current. The only additional equipment necessary to accomplish this is an a-c potentiometer attached to the shaft of the individual indicators. The elimination of the standard cell, which would be necessary if totalizing were done by direct current, is of importance. Most of the possibilities of totalizing have been used in this installation, such as totalizing of individual station generator loads, totalizing of loads of different frequencies, and the combining of system generation with loads carried on interconnections to show net power consumed on the system. Only the retransmitting of totalized indications back to generating stations was omitted. While this could readily be accomplished with the system adopted, it was not thought necessary.

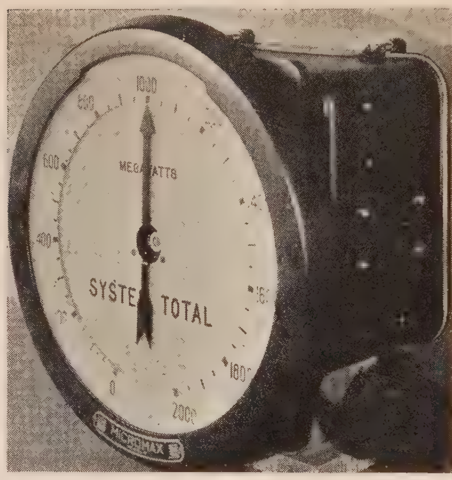

Fig. 4. Load indicator

Accuracy Obtained

An idea of the accuracy of the indications at the system operator's office may be obtained when it is understood that the indicators and recorders individually have a guaranteed accuracy of 0.33 per cent. As finally adjusted in the company laboratories the accuracy of the thermal converters is the same. Assuming the most improbable case wherein the individual errors are all in the same direction, let us determine the accumulated errors. At Hell Gate generating station during the normal evening load, generating capacity totalizing 300 megawatts will be on the line. The 5 thermal converters metering this load will introduce an error of 1 megawatt. In addition, the indicator on the system operator's board has a possible error of 0.33 per cent full scale reading (500 megawatts) which amounts to 1.67 megawatts, making a total possible error of 2.67 megawatts or 0.53 per cent on the 60-cycle Hell Gate indicator. Since the smallest division on this indicator represents 10 megawatts, the error of slightly over $^1/_4$ division is less than the error of reading.

Passing on now to a consideration of the next indicator which totalizes the Hudson Avenue sta-

tion load, we find that with a generating capacity of 540 megawatts connected to the line, the cumulative error in the thermal converters will be 1.8 megawatts. The Hudson Avenue indicator on the system operator's board with a scale of 800 megawatts has a possible error of 2.67 megawatts which, added to the converter error, gives a total of 4.47 megawatts or 0.56 per cent. The 60-cycle generation total indicator has a possible error of 3.33 megawatts based on the 1,000 megawatt scale. Adding all the above errors, a total possible error of 10.47 megawatts is obtained, which is slightly over 1 per cent of the full scale reading of the total 60-cycle generation indicator. Since the smallest division of this indicator represents 25 megawatts, the error of 10.47 megawatts is less than $^1/_2$ division, and is still within the error of reading.

In order to arrive at the possible error in the system total generated indicator, the same method of computing errors was applied to the 25-cycle load. This will give an accumulated error on the 25-cycle total indicator of 6.72 megawatts or 0.83 per cent. Adding this to the 60-cycle total error of 10.47 megawatts gives an accumulated error of 17.19 megawatts which is passed on to the system total indicator. This indicator with a scale of 1,600 megawatts will have an error of 5.33 megawatts. Therefore, the total possible error in the system total generated indicator is 22.5 megawatts, or less than $^1/_2$ division on this indicator. In terms of full scale reading, this error amounts to 1.4 per cent. It is evident, therefore, that at any point on the totalizing system, the accumulated errors are usually within the error of reading.

Standard telephone communication channels are used in every case to transmit the output of the thermal converters. Referring to Fig. 5, it will be seen that these channels vary in length from a few miles to 32 miles. The resistance of these channels is given in Table I.

Varying sizes of wire (No. 19 and No. 22) in the telephone channels and the fact that profile distances are given account for the lack of agreement between mileage and resistance.

Performance

Although no conclusion regarding the reliability of this equipment could be drawn from the satisfactory performance during the short period of its operation, it seems reasonable to expect little difficulty. The thermal converters have no moving parts, are mechanically strong and electrically well designed and should function correctly under all conditions which can reasonably be assumed. The potentiometer mechanism is essentially the same as that used in the temperature recorders, which have proved reliability by many years of satisfactory service. The telephone circuits have an excellent record of continuity.

Although the installation is too recent to enable its effect on operating economy to be measured, it is no exaggeration to say that it will contribute to economy. Before the installation of these meters, when the load on the regulating station varied, the operator at this station would report conditions to the system operator by telephone. The system operator would then by telephone issue instructions to operators in the base load stations to adjust load. Before these adjustments had been completed in the base load stations conditions in the regulating station might have changed so that the system operator's efforts to aid the regulating station were nullified. Moreover, the system operator was obliged to estimate the speed of the changes and to anticipate them if possible. Since the totalizing meters have been in service, the system operator has been able to distribute load changes so much more effectively that the number of telephone calls has been reduced by more than 75 per cent.

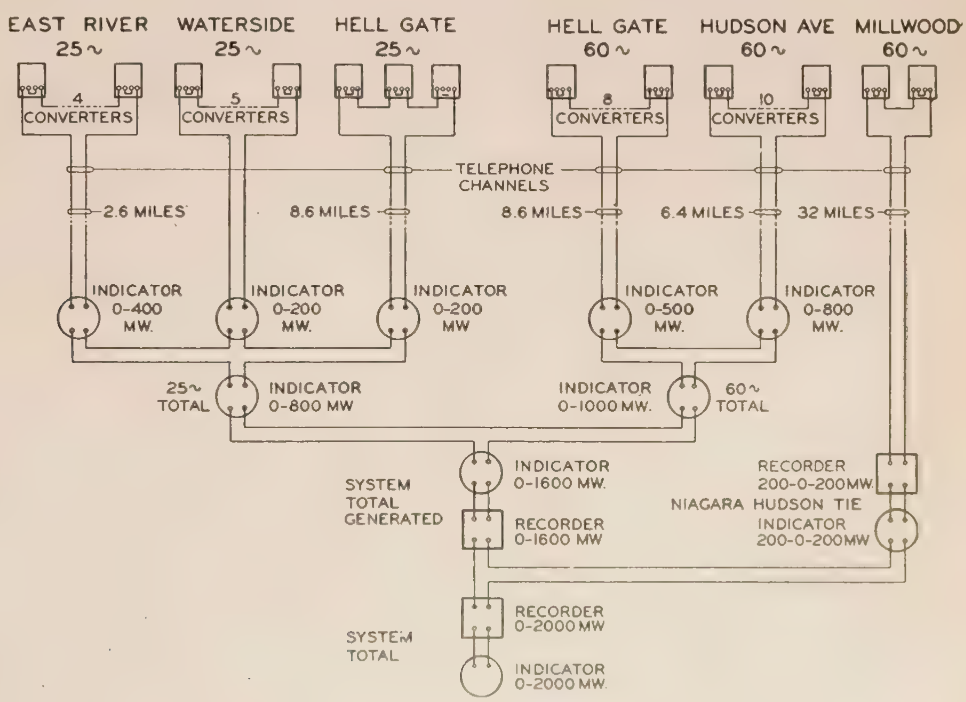

Fig. 5. Diagram of connections of the New York load totalizing system showing the method of combining the various load indications

MW—Megawatts

Iron Armored Aerial Communication Cable

This paper describes a study of the application of an iron armored aerial communication cable as an inductive coördination measure permitting a high voltage transmission line to occupy jointly for a distance of about 20 miles the same railroad right-of-way with telegraph and telephone circuits. Calculations are given indicating the induction to be expected on open wire communication circuits, and the degree of reduction afforded by several different designs of cables, both armored and non-armored. The effect of cable on the normal operation of the telegraph and telephone circuits carried through it also is considered.

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INCREASING PUBLIC DEMAND for power and communication services requires the maximum use of existing facilities, as well as the construction of new circuits. In this expansion of service, situations frequently arise where, because of congestion of wire facilities or other limitations of space, it is necessary for power and communication circuits to occupy rights-of-way which are not widely separated. To meet these situations new and more effective methods of inductive coördination must be developed.

A particularly difficult problem of this kind was encountered in the plans for constructing a new high tension transmission line. The number of possible routes for this line was limited and, although this route was not eventually selected, a complete investigation was made to determine the practicability of locating the power line along a railroad right-of-way already occupied by telephone and telegraph circuits. This paper deals with the study of the inductive effects in the proposed exposure, the application of suitable coördinative measures to the power line, the design of a communication cable which meets the unusual conditions imposed, and the results which may be expected from the use of such a cable.

These studies of the application of iron armored cable as a remedial measure, where communication circuits are subject to large induced voltages, indicate the following conclusions:

1. An iron armored cable of practical design can be made which will give a large reduction in induced voltage.

2. The efficiency of the cable as a shielding medium can be greatly increased by increasing the conductivity of the sheath, but to take full advantage of this shielding, the sheath must be terminated at the ends of the exposure through the equivalent of a very small impedance to ground.

3. An iron armored cable is applicable to both ground return telegraph circuits and to telephone circuits, and its effect on the normal operation of both classes of circuits is in general but little different from that of an equal length of non-armored cable.

4. An iron armored cable, although expensive, is a practical means of coördination in certain situations where other methods will not give a sufficient reduction in voltage. It is effective under both normal and abnormal operating conditions on the power system.

Description of Exposure

The proposal contemplated the construction of a twin circuit line supported on a bridge type structure overbuilding the railroad for a distance of about 20 miles. The line was designed for vertical arrangement of the phase conductors with 2 overhead ground wires.

The width of the right-of-way would not permit the use of open wire construction for the communication lead, so no study of possible coördination of open wire was made. Aerial construction supported on the same structures as the transmission line was preferred to underground to reduce the cost and to avoid electrolysis from d-c traction current.

There is at present on this railroad right-of-way a pole line carrying high speed multiplex printing telegraph circuits, land wire connections for transatlantic cable circuits, and telephone circuits used by the railroad for dispatching. Obviously, these facilities could not continue to operate under such severe exposure conditions unless unusually effective methods of coördination were applied to both the power and the communication circuits. The removal of the telegraph circuits to another route was considered, but this would not have been a complete solution of the problem since it was essential that the telephone circuits remain along the railroad.

Effect of Induction on Communication Circuits

The telegraph circuits in this exposure are normally operated with ground return and employ frequencies up to 60 cycles. Thus they are especially susceptive to 60-cycle induction and are also affected by 180-cycle voltages.

Telephone circuits are operated on metallic pairs with the earth forming no part of the circuit. Hence the induced voltages between wires can be largely reduced by transposing both sides of the pair. Telephone noise is caused by voice-frequency harmonics

Full text of a paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 1, 1934; released for publication March 25, 1934. *Not published in pamphlet form.*

the fundamental 60-cycle induction being relatively unimportant unless it is of sufficient magnitude to operate protective devices or become hazardous to equipment or personnel.

In this particular situation, there are 3 sources of induction arising from the normal operation of the power system, and since the measures which may be applied to reduce their effects are different, they are treated separately. The sources are as follows:

1. Direct induction from the balanced 3-phase currents due to unequal distances of the several phase conductors from the communication circuit. Transposition and proper arrangement of phases of multiple circuit lines carrying equal current per conductor are effective in reducing this type of induction. The latter measure is, of course, not effective when only one circuit is in service.

2. Secondary induction from currents flowing in the ground wire circuit. These currents are caused by direct induction from the balanced phase currents, and may be reduced by transposition and proper phase arrangement.

3. Induction from residual currents. These currents flow in a circuit consisting of the phase conductors in parallel, with return through the earth or other metallic paths. Residual currents are caused by unbalances in the system or triple harmonic voltages. Transpositions and phase arrangements have no influence on these inductive effects, except in so far as they may reduce unbalances in the line. Overhead ground wires and other shielding structures are effective in reducing induction from this source.

The magnitude of the induction from these different sources is indicated in Table I, together with the degree of reduction that can be secured by the various methods of coördination mentioned. The direct induction from balanced currents and that from the currents in the ground wires are both related to the phase wire current, and therefore the inductions from these 2 sources must be added vectorially. The twin circuit transmission line was designed for a full load current of 625 amp, hence this figure is taken as the basis for the calculations.

For the purpose of this study, a residual current of 6 amp is assumed; and, since its relationship to the load current is not known, the induction from this source has been added arithmetically to that resulting from the load current in order to get the total maximum induced voltage under normal operating conditions.

Calculations indicated that, in the event of a ground fault on one phase, a maximum current of 2,600 amp might be drawn through the exposure;

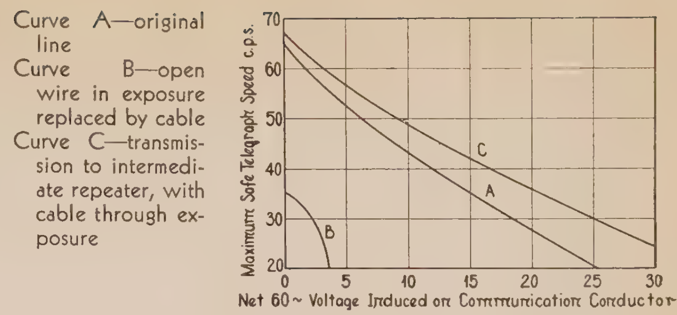


Fig. 1. Relation between telegraph transmitting frequency and induced voltage

therefore the calculated abnormal voltage is based upon this value. This fault current is a residual current and therefore its effect is reduced by the shielding effect of the ground wires, but it is not affected by transpositions. The calculated shield factor for the ground wires (0.67) is not so good as is usually secured with ground wires of this conductivity, because the phase conductors are about midway between the ground wires and the communication conductors.

In Fig. 1 are given the results of a study made to determine the effect of various amounts of induced voltage on the transmission speed of the multiplex telegraph circuits. It is apparent that measures in addition to those indicated in Table I must be provided if satisfactory coördination of these circuits is to be secured. A method suggested was the use of an iron armored cable for the communication conductors. To satisfy all the desired conditions of this particular case, it should accomplish the following:

1. Reduce the normal induced voltage as much as is economically justified. In the present case, it was recommended that the induced voltage with only a single power circuit in service, which is the more severe condition of operation, should be reduced from 170 volts to about 5.

2. Reduce the induced voltage under abnormal conditions from 18,600 volts to less than 900, which is the breakdown potential of the standard cable protectors.

3. Provide a sufficiently low impedance path from cable sheath to ground so that in case of contact with a phase conductor the communication cable would not be raised to such a voltage that its insulation would be broken down.

Table I—Calculated Open Circuit 60-Cycle Voltage Induced Along Communication Circuit Without Cable Shielding

Length of Exposure 20 miles; Earth Resistivity 100 meter-ohms; Efficiency of Transpositions 90%

	Normal Induction						Total Induction	
	From Balanced Current			From Residual Current*				
	Direct	Ground Wire	Total	Direct	Ground Wire	Total	Max. Normal	Max.** Abnormal
Twin Circuit Operation; 312.5 amp per phase								
No transpositions; horizontal arrangement	940	315	1,250	64	23	42	1,290	18,600
No transpositions; diagonal arrangement	101	37	64	64	23	42	106	18,600
Line transposed; diagonal arrangement	10	4	6	64	23	42	48	18,600
Single Circuit Operation; 625 amp per phase								
No transpositions; horizontal arrangement	990	290	1,270	64	23	42	1,310	
No transpositions; diagonal arrangement	990	290	1,270	64	23	42	1,310	
Line transposed; diagonal arrangement	99	29	127	64	23	42	169	

	Horizontal Arrangement		Vertical Arrangement	
	Circuit 1	Circuit 2	Circuit 1	Circuit 2
	Phase ....A	A	Phase ....A	C
	Phase ....B	B	Phase ....B	B
	Phase C	C	Phase C	A
	Horizontal arrangement		Diagonal arrangement	

* Assuming 6-amp residual current.
** Including shield factor of ground wires (0.67).

A large amount of theoretical and experimental work had been done on the shielding effect of cable sheaths, both armored and non-armored, and was available at the time of this study. The theory underlying much of this work has been described in a paper by H. R. Moore.[1] An equation is there given for the "shield factor" for any aerial communication cable grounded only at the 2 ends of the exposure. The shield factor (η) may be defined as the ratio of the resultant or shielded voltage to the initial or non-shielded voltage. Lower values of the shield factor thus indicate greater shielding. The equation is as follows:

$$\eta = \frac{r_{22} + R/l}{z_{22} + Z_{22}^\circ + R/l} \qquad (1)$$

Where

r_{22} = d-c resistance of cable sheath per unit length
z_{22} = internal impedance of cable sheath per unit length
Z_{22}° = external impedance of cable sheath per unit length
R = total resistance of grounding connections
l = length of exposure

The external self impedance Z_{22}° is the same as the impedance with ground return of a thin walled, perfectly conducting tube, closely fitted about the cable sheath and grounded at the ends through a resistanceless connection. It is dependent upon the radius of the sheath, its position with respect to the earth, and the earth resistivity. The magnitude of the external self-impedance may be determined from Carson's equation.[2]

The internal self impedance z_{22} depends solely upon the composition of the cable sheath, and consists of the sheath d-c resistance r_{22} plus contributions due to the flux within the iron armor. The latter comprise a resistance increment Δr_{22} due to hysteresis, eddy currents, and skin effect, and a reactance increment X_{22} due to the linkages of the flux within the boundaries of the iron. Thus

$$z_{22} = r_{22} + \Delta r_{22} + jX_{22} \qquad (2)$$

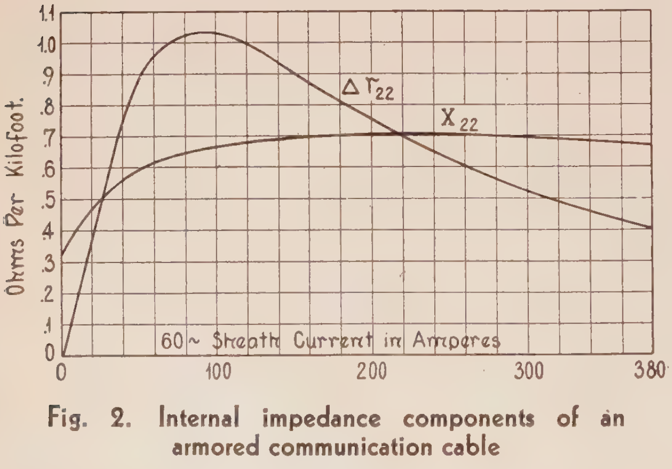


Fig. 2. Internal impedance components of an armored communication cable

Armor comprising 2 steel tapes each 2x0.04 in.; main radius of armor, 1.3 in.; Δr_{22} does not include d-c resistance

The values of Δr_{22} and X_{22} depend upon the current in the cable sheath and its frequency, as well as on the characteristics of the iron armor, its dimensions and position. These values can best be determined experimentally, and curves for a representative armored cable are given in Fig. 2.

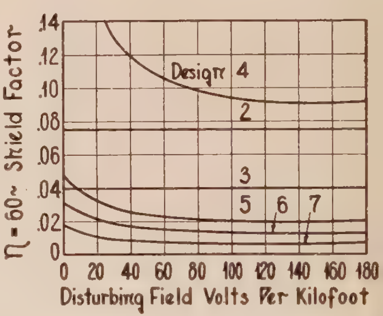
Combining equations (1) and (2), the shield factor may be expressed as

$$\eta = \frac{r_{22} + R/l}{r_{22} + \Delta r_{22} + jX_{22} + Z_{22}^\circ + R/l} \qquad (3)$$

It is evident that the shield factor may be reduced either by decreasing the ground resistance R or by reducing the sheath resistance r_{22}. The same result can be obtained by increasing the internal impedance components Δr_{22} and X_{22}, but the external impedance Z_{22} is usually fixed rather definitely by the conditions of the problem. The d-c resistance of the sheath may be reduced by introducing copper conductors in parallel with the lead sheath, and the quantities Δr_{22} and X_{22} may be controlled by the type of armor employed. The problem is to determine the most economical combination of iron armoring and copper shielding capable of providing the desired degree of reduction.

Fig. 3. Relation between shield factor and disturbing field

Cable comprising 38 pairs of No. 13 A.W.G.; earth resistance 100 meter-ohms; sheath perfectly grounded
Armoring comprises 2 iron tapes each 2x0.04 in.



Design No. 1 (not shown) non-armored cable; shielding copper, none; sheath d-c resistance (r_{22}), 0.135 ohm per 1,000 ft
Design No. 2—non-armored cable; shielding copper, 500,000 cir mils; sheath resistance (r_{22}), 0.018 ohm per 1,000 ft
Design No. 3—non-armored cable; shielding copper, 1,000,000 cir mils; sheath resistance (r_{22}), 0.0097 ohm per 1,000 ft
Design No. 4—armored cable; shielding copper, none; sheath resistance (r_{22}), 0.135 ohm per 1,000 ft
Design No. 5—armored cable shielding copper, 300,000 cir mils; sheath resistance (r_{22}), 0.028 ohm per 1,000 ft
Design No. 6—armored cable; shielding copper, 500,000 cir mils; sheath d-c resistance (r_{22}), 0.018 ohm per 1,000 ft
Design No. 7—armored cable; shielding copper, 1,000,000 cir mils; sheath d-c resistance (r_{22}), 0.0097 ohm per 1,000 ft

Fig. 3 shows the shield factor, calculated from eq 3, for several non-armored and armored cables containing various amounts of shielding copper. The shield factors are plotted against the disturbing field intensity, i. e., the voltage which would be induced along the conductor in the absence of any cable shielding. It is seen that non-armored cables provide uniform shielding regardless of the value of the disturbing field. The armored cables give better shielding as the disturbing field is increased, up to about 150 volts per 1,000 ft.

This variation in the shield factor is caused by the non-linear relation between the sheath internal impedance and the sheath current. The induced sheath current depends upon the magnitude of the disturbing field and the self impedance of the sheath

circuit; and the internal component of this self impedance depends, in turn, upon the value of the current. As a result of this mutual interdependence, the shield factor corresponding to a given disturbing field intensity can be determined only by a laborious cut and try solution. The curves in Fig. 3 were prepared in order to avoid this method. First several arbitrary values of sheath current I_2 were chosen and the corresponding values of Δr_{22} and X_{22} were obtained from Fig. 2. Then assuming a zero grounding resistance R, the disturbing fields

$$E_2 = I_2 (r_{22} + \Delta r_{22} + jX_{22} + Z_{22}^{\circ})$$

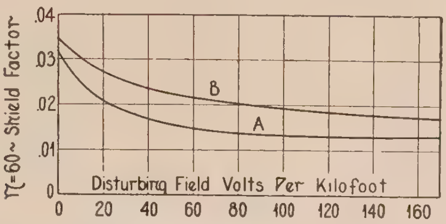
which would produce these sheath currents were computed. Using the same values of Δr_{22} and X_{22}, the shield factors were calculated from eq 3 and plotted (η vs. E_2) for each cable.

Table II—Effect of Type and Conductivity of Cable Sheaths on 60-Cycle Induced Voltages Given in Table I

Design No.	Shielding Copper (cir mils)	Cost Factor	Shield Factor* Max. Normal	Shield Factor* Max. Abnormal	Remaining Voltage Max.** Normal	Remaining Voltage Max. Abnormal
Non-Armored Cable						
1	None	0.49	0.480	0.480	81.1	8,930
2	500,000	0.86	0.075	0.075	12.7	1,390
3	1,000,000	1.20	0.040	0.040	6.8	740
Armored Cable						
4	None	0.64	0.213	0.091	36.0	1,690
5	300,000	0.89	0.048	0.020	8.1	370
6	500,000	1.00	0.031	0.013	5.2	240
7	1,000,000	1.34	0.017	0.007	2.9	130

* Assuming no resistance from sheath to ground.
** Single circuit operation, with power line transposed.

Fig. 4. Effect of cable termination



Curve A—cable grounded at ends of exposure through zero ohms
Curve B—cable extended 1 mile beyond each end of exposure and grounded at ends and at each tower
Cable Design No. 6; 20-mile exposure; 15 towers per mile; tower footing resistance 10 ohms each; earth resistivity 100 meter-ohms

Due to the small separations existing in this exposure, it was considered desirable to investigate the effect of the cable sheath current in inducing additional currents in the ground wires on the power line. A calculation was made by the method of successive approximations to determine this effect. The results indicated that the mutual interaction between the circuits introduces a modification of only 5 per cent in the induced voltages. Accordingly, this refinement was neglected.

Table II was prepared to show the shielding to be expected from each of the cable designs in Fig. 3 under 2 important conditions. In this particular exposure, the maximum disturbing field, as given in Table I, is about 175 volts per 1,000 ft for abnormals and 1.6 volts per 1,000 ft for normal single circuit operation. Cable designs Nos. 3 and 6 both provide sufficient shielding to reduce this induction to the approximate condition desired, but design No. 6 was accepted as the better solution because of lower cost, and because it provides greater shielding at the higher intensities of disturbing field. Design No. 6 will also be less influenced by the resistance of the grounding connections than No. 3, since the d-c resistance of a 20-mile length of cable No. 6 is 1.9 ohms while the resistance of cable No. 3 is only about 1.0 ohm.

Effect of Sheath Grounding Connections

The shield factors presented in Fig. 3 are based on the assumption that the cable sheath will be provided with perfect ground connections at the ends of the exposure. Actually the character of the terrain in the vicinity of this exposure is such that it would be impracticable to secure and maintain ground connections with the extremely low resistance required. In practice, the sheath would be grounded at each tower through the tower footing resistance, and the cable would be extended some distance beyond the ends of the exposure. The theoretical considerations applying to this problem are the same as those for an underground cable with distributed leakance to ground, the assumption being that the tower footings are of uniform resistance.

Calculations were made to determine the degree to which the shielding from such a cable can be made to approach that obtainable when the sheath is perfectly grounded. In Fig. 4 is shown a comparison between the shield factor for cable No. 6 when solidly grounded, and when grounded through 15 towers per mile and extended one mile beyond each end of the exposure. The towers were assumed to have a footing resistance of 10 ohms each. It is seen that, for the normal induction of 1.6 volts per 1,000 ft, the shield factor is within 10 per cent of that obtainable under ideal conditions. For the abnormal induction of 175 volts per 1,000 ft, the shield factor is 30 per cent greater than that provided by a perfectly grounded sheath. Reference to Table II indicates that neither of these increases is sufficient to make the resultant voltages exceed the design requirements.

Recommended Cable Design

The recommended cable, which is shown in Fig. 5, contains 19 quads of 13-gauge conductors. It is provided with paper insulation to withstand 1,200 volts rms between conductors and 3,500 volts rms between the conductors and sheath. Over this insulation, and in contact with the lead sheath, is spiraled 500,000 cir mils of bare copper wire to provide the necessary additional sheath conductivity. Contact between the spiraled layer and the sheath is afforded by a helical winding of thin copper strip, partly overlaid with paper. This construction prevents the bare copper winding from adhering to the

lead sheath, which might cause the latter to tear when it is bent. External protection of the lead sheath is secured by means of a paper wrapping and a covering of jute over which are spiraled 2 galvanized iron tapes each 40 mils in thickness and 2 in. in width. They are put on in 2 layers with a $^1/_2$-in. gap between turns and with gaps overlapped, giving an over-all diameter to the cable of $2^3/_4$ in. The weight of the cable, 10.66 lb per ft, necessitates the use of 2 cable messengers and catenary construction.

Voltage Between Cable Sheath and Conductors in Case of Contact With a Phase Wire

Operating experience with transmission lines, of the same grade of construction as this line, has indicated that the possibility of a conductor falling is remote, but because of the location of the cable, consideration must be given to the effects which might result from a direct contact between the sheath and a fallen phase conductor. In the event of such a contact, the cable sheath will be raised to a potential above earth equal to the product of the fault current and the impedance of the sheath to ground. This potential will exist between the sheath and the internal conductors at the point of contact, but will not appear along the conductors or at the terminals as will the induced voltage. The voltage of the sheath above ground in case of direct contact was calculated for two locations of the fault. In both cases the fault currents were calculated for the arrangement of lines, station capacity, etc., giving the largest fault current. The impedance of the cable sheath to ground was obtained by assuming 15 towers per mile, each with a tower footing resistance of 10 ohms. The computed voltage of the sheath above ground and internal conductors for contact either in the middle of a span or at a tower is given below.

Location of Fault at End of Line to Give	Fault Current (Amp)	Voltage of Sheath to Ground: Contact in Middle of Span	Voltage of Sheath to Ground: Contact at Tower
Max Current	6,400	3,650	2,400
Min Current	2,600	1,480	980

Effect of Cable on Normal Circuit Operation

Telegraph Circuits. For telegraph transmission open wire construction is preferred to cable, partly for financial reasons and partly because any kind of cable has higher transmission losses than an open wire circuit. For multiplex circuits, a mile of 13-gauge cable is equivalent to about 5 miles of open wire; and for carrier circuits, the cable loss is from 6 to 10 times that of open wire. The additional losses caused by the insertion of over 20 miles of 13-gauge cable in this case will require the establishment of an additional repeater point for the telegraph circuits. Figure 1, previously discussed, shows a comparison of the estimated speeds of transmission, with various magnitudes of induced voltage, for the present open wire circuit, and for the modified circuit with and without an added repeater.

This investigation indicates that the effect of the iron armored cable on normal telegraph operation is practically the same as that of an equal length of non-armored cable. The only change in the constants of the circuits is a slight difference in the ground-return self impedance of the telegraph circuits due to the iron armor, a modification which is not important.

Some generation of harmonics is to be expected from the current in the non-linear impedance of the cable sheath circuit, but theoretical and laboratory studies indicate that the magnitude of these harmonics is so small that they will have no appreciable effect on the operation of the telegraph circuits.

Telephone Circuits. Earlier in the paper attention was called to the fact that the voltage induced between the sides of the telephone circuits can be reduced to small values by transposition. The use of cable provides continuously transposed circuits so that the voltage induced between the wires making up the sides of the circuit is reduced practically to zero. Since telephone circuits operate at frequencies higher than the fundamental of the power system, only harmonic frequencies cause an appreciable amount of noise. An examination of eq 3 indicates that the shield factor decreases, as the frequency of the induced voltage increases. Thus an increased efficiency of shielding exists at the higher frequencies, compensating in part for the greater coupling at these frequencies.

There will be some high frequency voltages appearing along the telephone conductors due to harmonic generation in the cable sheath, but a low impedance path is provided for the harmonic currents in the sheath ground-return circuit; thus the voltages along the internal conductors will be small. Furthermore, such induced voltages are along the conductors in parallel and not between the sides of the circuit, so any current producing noise will be

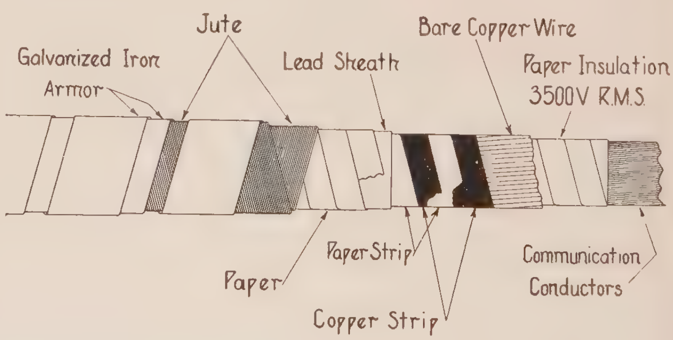


Fig. 5. Recommended design for armored aerial cable

due to this voltage acting on unbalances in the telephone circuit. With the type of telephone terminal equipment normally used with this type of circuit and the high degree of balance in communication cable, the noise from this source will be so small that it cannot be easily measured.

As in the case of the telegraph circuits, the use of

cable introduces additional losses in the telephone circuits. Since some of the open wire telephone circuits are already long and are working near their limits of satisfactory operation, the addition of cable will require the insertion of loading coils and repeaters to compensate for losses and distortion.

REFERENCES

1. IRON SHIELDING FOR TELEPHONE CABLES, H. R. Moore. ELEC. ENGG., Feb. 1934, p. 274–80.
2. WAVE PROPAGATION IN OVERHEAD WIRES WITH GROUND RETURN. *Bell Syst. Tech. Jl.*, Oct. 1926.

The Suspension Insulator

Improvements and strengths of suspension insulators which have been attained since the publication in 1931 of a paper by the present author are outlined in this paper. Details of the improvements which have been made since that time are discussed herein, and considerable data on the strength of suspension insulators of different types are given.

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A PREVIOUS paper on the development of the porcelain insulator, as of September 1930, told of the step-by-step process of suspension insulator improvement. (See "Development of the Porcelain Insulator," by K. A. Hawley, A.I.E.E. TRANS., v. 50, 1931, page 47–51.) Progress has been made in the meantime calling for a further report on this subject.

STRENGTH RATING AND SAFETY FACTORS

Insulators are given strength ratings based upon quick laboratory tests according to the A.I.E.E. Standards 41–154. The question is frequently asked as to how these are to be interpreted in terms of time loadings, what the elastic limits will be, and what safety factors are to be used. The purpose of this paper is to discuss these further developments and to establish insulator strengths in terms of their ratings.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 13, 1934; released for publication April 30, 1934. *Not published in pamphlet form.*

NEED FOR HIGHER STRENGTH

The earlier insulators, as reported, had a strength under sustained load of barely 7,000 lb before fracture and electrical failure would occur. Many thousands of these insulators are in service giving an excellent account of themselves. Yet occasionally through overloads breakages have occurred. We know of at least 4 separate cases, well scattered from coast to coast, where insulators of these strengths and of various origin have been literally pulled apart by excessive ice loadings.

It was shown in the previous paper how, by a slight change in the hardware structure, this strength was increased first to 10,000 lb and then by further checking and balancing to 17,000 lb before failure on time loading tests.

RATINGS OF INSULATORS INVESTIGATED

The insulators covered are those which would be given A.I.E.E. strength ratings of 15,000, 18,000, 25,000, and 30,000 lb, respectively. While more complete tests have been made upon the 18,000 and 30,000 lb types than upon the others, efforts at strength standardization among the manufacturers are bringing the other 2 to the fore.

IMPROVEMENT DETAILS

After the initial work of providing resilience between the inner surface of the cap and the cement, as described in the previous paper, the increase in strengths of suspension insulators had been largely a matter of increasing head heights. An extensive series of tests and research culminating around 1931 showed the value of slight modifications of design. Notable among these were improved methods of manufacture allowing the insulator head to be made with a more nearly vertical side wall on the outside and in the pinhole, greater accuracy in glaze fit, the adoption of definitely graded "sand" for the cement grips, and the reglazing of these cement grips. This work has been fully covered in the previous A.I.E.E. paper by the author and in articles by D. H. Rowland (see "The Influence of Glaze on Insulator Strength," *G. E. Rev.*, v. 32, 1929, p. 136–8; and "Recent Improvements in High-Voltage Insulator Design," v. 33, 1930, p. 384–7). This allowed the height of the head to be decreased without sacrifice of strength and added considerably to the uniformity of the insulator strengths.

The cost of firing and consequently the cost of the completed insulator are to a certain large extent dependent upon over-all height. The reduction in the head height allows fuller porcelain hood depth, more rugged exposed parts, greater leakage surface, and a measurable if not marked increase in impulse

arc-over value, features which have all been incorporated in the present standard suspension insulator.

It has been recognized for years that the centering of the bolt within the pinhole had a direct influence on the strength of the insulator. If the edge of the bolt bore upon the porcelain, concentrated loads upon the porcelain were likely to cause cracking and failure at a low value. This difficulty has been overcome by the use of a star shaped pad or washer of impregnated paper glued to the top of the bolt. This washer is so designed to allow free flowing of the cement past it as the bolt is introduced into the cement filled pinhole. Its star shaped prongs are adequately flexible to enter the hole and yet quite accurately center the bolt. The adoption of this type of washer in preference to the old round washer which merely covered the bolt head has greatly contributed to the present marked uniformity found on routine test.

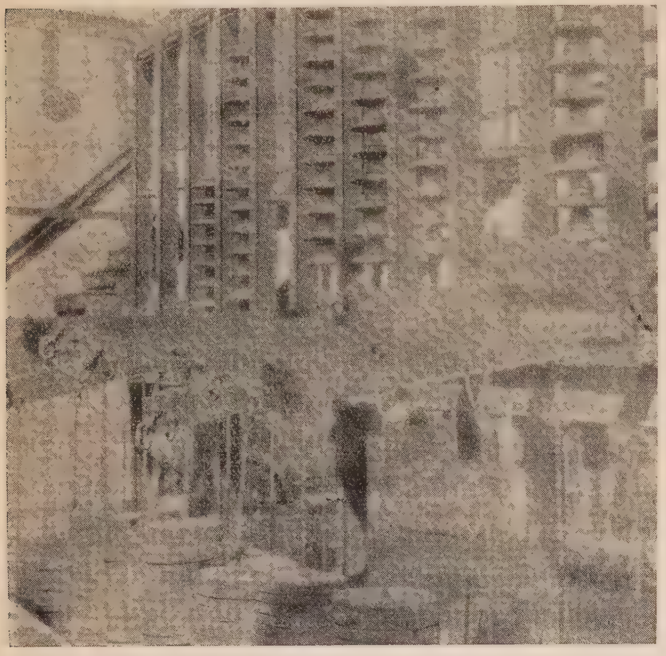

Fig. 1. Outdoor test frame at Baltimore, Md., for making duration strength tests on suspension insulators

Table I—Tests on Insulators, 18,000-lb Rating, Single-Stepped Bolt

Test	Cement 24 Days Old M. & E.	Ultimate
1	23,800 lb	23,800 lb
2	24,700 lb	24,700 lb
3	23,000 lb	25,000 lb
4	24,400 lb	24,400 lb

Another feature that has always introduced a variable had been the need for exact placement of the edge of the sand belt. If the edge of the sand belt falls within the area of load application, slippage of the cement upon the smooth glazed unsanded surface may throw an excess load directly upon this point. The flexibility of the cap lip adequately cares for the loading upon the outside of the head at the lower edge of the sand belt.

However, locating the inner edge of the sand belt within the pinhole at a definite point is difficult for even the most skilled operators. This difficulty has been overcome by extending the sand belt completely down the walls and over the bottom of the pinhole.

The Multiple-Stepped Bolt

The construction of an insulator can be likened to an arch in which the lower part of the cap forms the abutments with the bolt for a keystone. The conception indicates the requirements in bolt design. A reduction in the height of the dome necessitates a reduction in the height of the keystone as represented by the stepped top end of the bolt. If the bottom step of the bolt comes below the level of the abutment of the arch we have a condition in which the tendency is for the arch to turn inside out much as the bottom of an oil can turns when pressed. The insulator, however, not being of flexible material like the oil can, cannot bend and consequently breaks. This is obviated by the number of steps used on the bolt.

The shape of the stepped bearing surfaces of the bolts has been the subject of many studies. The cement and porcelain, having almost identical moduli of elasticity, structurally work together as a single piece. Small but positive cement thickness is needed to distribute the load through the porcelain. Tests with the single-stepped bolts with curved or straight surfaces have shown no advantages in their favor. Tests results listed in Table I give actual values for insulators with single curved stepped bolts and may be compared with those given in Table II for insulators with 2-stepped bolts.

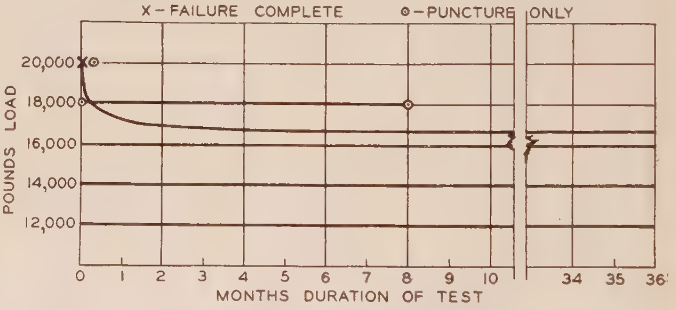

Fig. 2. Probable life of 18,000-lb class insulators under stress

Insulators of 18,000-lb rating and with 2-stepped bolts were also tested to demonstrate:

a. The effectiveness of the 2-stepped bolt.
b. The uniformity of strength with well set cement.

Those who work with cement know the varying

rate of cement setting prevents uniform strengths with relatively green cement. Many variables affect the rate of setting, such as size of cement grains, time between mixing and using of cement, and the temperature of the insulator during the entire cementing period. Table II, an excerpt from a typical test report, will make this point clear. The insulators in each batch were identical except in the length of time elapsed between assembly and testing.

Table II—Tests on Insulators, 18,000-lb Rating, 2-Stepped Bolts

Test	18 Day Cement M. & E.	18 Day Cement Ultimate	28 Day Cement M. & E.	28 Day Cement Ultimate
1	22,000 lb	25,900 lb	27,150 lb	27,150 lb
2	19,900 lb	29,000 lb	27,100 lb	27,100 lb
3	23,450 lb	28,300 lb	27,750 lb	27,750 lb
4	22,300 lb	27,700 lb	26,100 lb	26,100 lb
5	24,350 lb	26,200 lb	25,000 lb	26,850 lb
6	27,900 lb	28,400 lb	26,800 lb	26,800 lb
High	27,900 lb	29,000 lb	27,750 lb	27,750 lb
Low	19,900 lb	25,900 lb	25,000 lb	26,100 lb
Avg.	23,308 lb	27,583 lb	26,650 lb	26,958 lb

Repeated tests along these same lines have given parallel results.

A period of tests extending back for over a decade has invariably shown more uniform results with the multiple step bolt, 2, 3, or 4 steps according to the depth of the pinhole. In addition to this, failures in service of insulators assembled with the one step bolt have definitely indicated the inadvisability of large masses of cement in the pinhole. These masses are reduced to a minimum by means of a correctly designed multiple-step bolt.

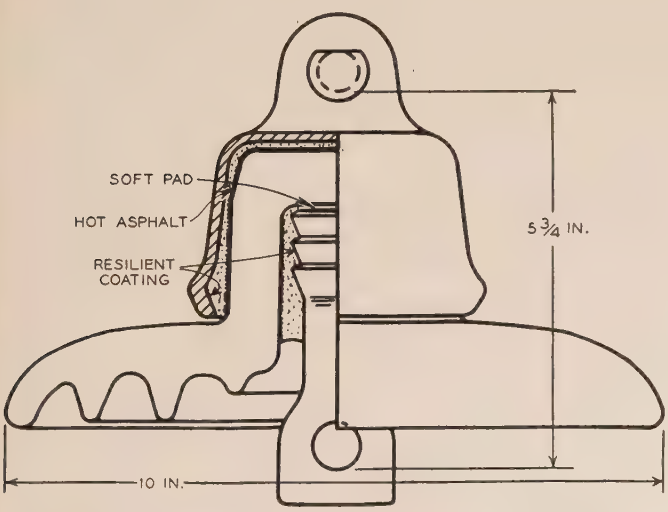

Fig. 3. Details of construction of 18,000-lb suspension insulator

Safety Feature of Cap and Pin Insulators

One thing that has been very noticeable on all these tests and which has borne out field experience is that with the cemented cap and pin insulator the overlap of the 2 is such that the line will be held in the air even should porcelain breakage occur. This is most important where the dropping of a conductor can in any way be a hazard. This is serious enough with the ordinary transmission line but becomes of prime importance with trolleys over electrified railways where moving equipment is likely to encounter such dropped conductors.

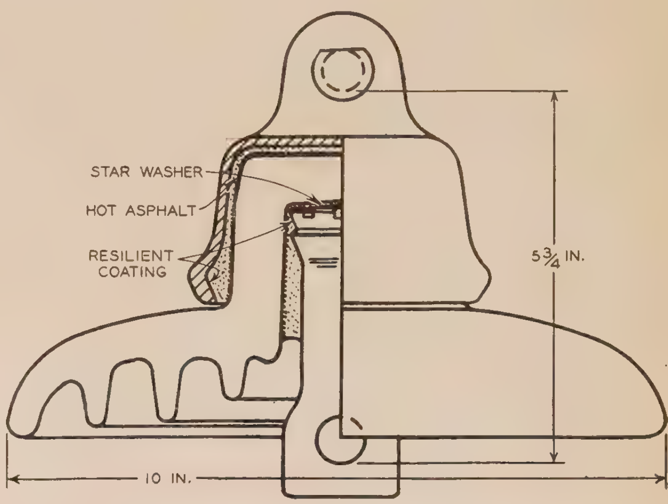

Fig. 4. Details of construction of 15,000-lb insulator

Check tests to show that standard suspension insulators maintain their full strength even when damaged by external violence have been conducted. The hoods were completely broken from 6 15,000-lb insulators and mechanical tests were then made with results as shown in Table III.

Table III—Mechanical Tests on 15,000-lb Insulators

Unit No. 1	16,550 lb	Unit No. 4	18,350 lb
Unit No. 2	15,750 lb	Unit No. 5	16,500 lb
Unit No. 3	18,400 lb	Unit No. 6	17,200 lb

Duration Tests

The previous paper showed a strength of 17,000 lb per unit with load increments of 1,000 lb per day for the 18,000-lb rated insulator. Subsequent tests upon improved units have shown strengths on similar tests varying from 23,000 to 27,000 lb.

An effort to establish through a long time life test the maximum load that the insulator will carry through all weather conditions has been made by exposing several strings of insulators at different loads in the out-of-door testing frames at Baltimore, Md.

While no record has been kept of freezing cycles passed through at the point of exposure, experience has shown that for this territory there will be a great number of alternate freezings and thawings each year. The past 2 years have been above the average in rain fall, each of about 50 in., quite uniformly distributed

through the year. The cement within the insulators would not at any time be thoroughly dried, but instead would be moist and active chemically if at all. Considerable hot weather, up to 100 deg F also was experienced.

Duration tests in the outdoor frame, Fig. 1, on similar insulators are given below. Individual units under the duration test are given frequent tests at flashover while under load.

18,000-Lb Rating

Test No. 1

6 units at 5,000 lb placed in frame September 13, 1928.
Removed from old frame, September 23, 1929.
Placed in new frame, February 4, 1930.
Still without loss.

Test No. 2

3 units at 10,000 lb placed in frame March 20, 1931.
3 units at 12,000 lb placed in frame March 20, 1931.
6 units at 14,000 lb placed in frame March 20, 1931.
6 units at 16,000 lb placed in frame March 20, 1931.

The consideration of laboratory tests led us to believe that the 10 and 12,000-lb loads were insufficient to give any definite indications and these were accordingly discontinued on May 4, 1931. The remaining 6 units at 14,000 lb and the 6 units at 16,000 lb were continued on test and are still intact.

Test No. 3

3 units at 18,000 lb placed in frame March 20, 1931.
No. 1 punctured March 21, 1931. Broke March 23.
No. 2 punctured November 9, 1931.
No. 3 O. K. electrically and mechanically September 14, 1932, when test was stopped.

Test No. 4

3 units at 20,000 lb placed in frame March 20, 1931.
No. 3 broke promptly.
No. 1 punctured.
No. 2 O. K. July 11, 1931, test stopped.

Insulators Having 2-Step Bolts

The insulators shown in the preceding tabulation of duration tests were slightly higher in the head than the present standard and accordingly employed a 3-step bolt. (See Fig. 3.) Similar tests on the revised insulators (See Fig. 4) which employ 2-step bolts follow:

Test No. 5

12 units at 14,000 lb placed in frame September 21, 1932.
12 units at 16,000 lb placed in frame September 21, 1932.

All units have been regularly flashed over individually while under load and are still mechanically and electrically perfect.

The above test results are shown graphically in Fig. 2, indicating clearly a probable continuous life at more than 16,000 lb loading for the 18,000-lb rated unit.

30,000-Lb Rating

Insulators of the higher strength rating, cataloged at 25,000 but more properly of 30,000-lb A.I.E.E. rating have also been tested in the out-of-door test frame with the following results.

Increment Tests

A typical test using the 1,000 lb per day increment method, beginning at 20,000 lb shows first electrical failure at 33,000 lb. (Test report, June 10, 1930.)

Continuous Tests

Test No. 6

12 units at 19,000 lb placed in frame June 12, 1931.
1 unit punctured September 24, 1931. (Without centering washer.)
Test is continuing and remaining units are still good.
12 units at 19,000 lb placed in frame June 12, 1931.
1 unit punctured January 2, 1934. (Without centering washer.)
Test is continuing and remaining units are still good.
12 units at 20,000 lb placed in frame June 12, 1931 without failure to date. (Without centering washer.)

Test No. 7

12 units at 23,000 lb placed in frame June 18, 1932.
12 units at 23,000 lb placed in frame June 18, 1932.
12 units at 25,000 lb placed in frame June 18, 1932.
12 units at 25,000 lb placed in frame June 25, 1932.
These insulators assembled with the star centering washer are still intact.

It is evident from these tests that the 30,000-lb insulator has a continuous strength of at least 25,000 lb when assembled with the centering washer as previously described.

15,000-Lb Rating

Two strings of 6 units at 15,000 lb rated strength placed in frame at 6,000 lb increasing loads each working day 1,000 lb. First failure in string No. 1, one unit punctured, load 15,000 lb, total time elapsed 18 days. Second string, one unit punctured. Load 16,000 lb. Time elapsed 20 days.
Further strings are on straight duration test at 12,000, 13,000, 14,000, and 16,000 lb but insufficient time has elapsed to the present for any definite results to be given. A comparison of the strength values obtained from quick pull tests on well seasoned units and duration tests show a very satisfactory ratio between the 2.

25,000-Lb Rating

Similar increment tests upon the 25,000-lb average rated insulator shows first electrical failure at 25,000 lb.

Résumé

The results of the above increment and continuous loading tests are shown in Table IV.

Table IV—Summary of Results of Tests

Rating Pounds	1,000 Lb per Day Increment Tests, First Elec. Failure	Continuous Load Test Without Failure
15,000	15,000 lb	
18,000	23,000 lb	16,000 lb
25,000	25,000 lb	
30,000	33,000 lb	above 25,000 lb

Suspension insulators of the cemented cap and pin types may be used with safety factors based upon their rating that would be considered reasonable with any structural material.

Radio Influence Insulator Characteristics

Insulators on high voltage lines may cause radio interference by the arcing of the insulator charging current. A copper oxide glaze for new insulators has been developed to prevent this arcing; treatment of old insulators with special compounds to exclude air is reported as helpful. Suspension insulators are found to require no treatment.

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TRANSMISSION and distribution lines with their auxiliary apparatus may be and sometimes are the source of disturbing radio frequency voltage with broadcast programs. Pin type insulators, for transmission and the higher distribution voltages, in good serviceable condition, are generally considered free from such disturbance but there may be cases where they are the source of trouble. Field investigations[1] show that insulators on lower voltage distribution are a minor contributing factor.

The radio influence characteristics of insulators have been investigated during recent years by the insulator manufacturers and some of the college laboratories[2] and treatments have been developed for improving their performance. (The term "radio influence" is used to describe that characteristic of apparatus or circuit which produces radio frequency voltages and that may, under certain conditions, cause interference with radio reception.) In general, the principal facts determined to date are as follows:

1. Pin type, apparatus type, and suspension type insulators, at various voltages, generate energy at broadcast frequencies.

2. In normal application and operation the energy output from insulators may produce voltages which may cause interference with broadcast reception, depending upon the coupling and sensitivity of the receiver.

3. The output of insulators or any device of this nature depends upon the impedance at broadcast frequency of the circuit to which they are connected; a grounded or ungrounded supporting pin.

4. Through several years' development of metallic glaze, a copper oxide glaze has been produced that fits into the regular manufacturing process of insulators; provides a treatment that improves the output characteristics of pin type and apparatus type insulators; and has been demonstrated by accelerated life tests to be permanent and effective.

5. The performance of suspension insulators is such that treatment does not appear to be required.

6. Filling the wire grooves and corona spaces on pin type and apparatus type insulators with asphalt emulsion or similar materials gives a temporary treatment, depending upon the life of the materials, that improves the radio influence characteristics of such insulators now in service.

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 26, 1934; released for publication April 13, 1934. *Not published in pamphlet form.*

Causes and Detection of Interference

The primary cause of radio frequency voltage from a pin type insulator is the arcing flow of charging current from the conductor and tie wire to the insulator and in some cases from the insulator to the pin in the pin hole. A very high resistance exists in the contact between the conductor and tie wire and the ordinary glazed surface of an insulator. The minute irregularities of the surface in contact form small gaps across which the current discharges, generating a radio signal in a manner similar to the old type spark gap radio transmitters. The output is low, largely because of the high internal impedance of the insulator. There may be other causes, such as corona between parts of the insulator or bad service conditions of dirt and moisture permitting the formation of leakage streamers. In normal operation, however, the primary cause as reviewed accounts for most of the disturbance.

The absence of standards for tests and evaluation of results in the early work did not permit an exact nor satisfactory comparison of the data obtained by the various investigators. Within recent months such standards[3] have been determined and tests made in accordance with these standards should permit such correlation.

The circuit used for determining the radio influence characteristics of insulators is shown in Fig. 1. All of the tests were made at a frequency of 1,000 kc. The device under test, in this case the insulator, generates energy at broadcast frequency

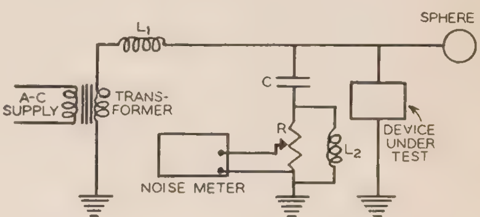


Fig. 1. Circuit for determining radio frequency influence of a device

when potential is applied. This is readily passed by condenser C, producing a drop across the resistance, R. This potential is measured by the noise meter in which it is balanced to the output of a calibrated signal generator. In this circuit, the high impedance of radio frequency choke coil $L1$ practically gives the effect of an open end line and resistance R determines the impedance to ground. With a value of R of 250 ohms the measured impedance of the circuit at 1,000 kc was 250 ohms. Radio frequency choke coil $L2$ by-passes the 60-cycle charging current of the condenser and acts as a safeguard to the operator and noise meter in case an

open circuit occurs through the resistance R.

Attention is called to the importance of circuit impedance at the broadcast frequencies upon the radio frequency output. Thus for an impedance of 100 ohms the output is approximately 15 per cent of that for an impedance of 500 ohms.

Another factor affecting the output is a grounded or ungrounded supporting or insulator pin. The curves, Fig. 2, illustrate the effect of circuit impedance on the output of a 66-kv pin type insulator with a grounded pin. Fig. 3 illustrates the same characteristics for the same insulator with an ungrounded pin. Table I shows the output values for grounded and ungrounded pins at normal operating voltage to ground. It also shows the values for the same insulators with a treatment for improving the performance.

Table I—Radio Frequency Output of 66-kv and 33-kv Pin Type Insulators With Regular Glaze and Treated Glaze at Normal Operating Voltage to Ground With Grounded and Ungrounded Pins

		Microvolt Output for Circuit Impedance of		
Insulator	Pin	100	250	500 ohms
66 kv with regular glaze	Grounded	4,200	12,600	27,400
38 kv to ground	Ungrounded	450	1,290	2,500
66 kv with treated glaze	Grounded	*	*	*
38 kv to ground	Ungrounded	*	*	*
33 kv with regular glaze	Grounded	2,880	8,500	17,000
19 kv to ground	Ungrounded	115	310	600
33 kv with treated glaze	Grounded	*	*	*
19 kv to ground	Ungrounded	*	*	*

* Less than 5.

The effect of the performance upon broadcast reception depends upon the propagation of the signal, its modulation and coupling and the sensitivity of the receiver. So many variables are encountered in these factors that a measure of the uniform effect on reception seems remote. To obtain an indication of the audible effect of such characteristics with very close coupling and high sensitivity of receiver, a tuned loop was located symmetrically between the conductor and ground within 8 ft of the insulator and connected to a receiver with a sensitivity of 2 microvolts per meter. Voltage was applied to the insulator and increased until the interference was just audible with full amplification in an earphone set. The sensitivity of this same receiver is 5 microvolts per meter when connected as in Fig. 1. To obtain similar audible effect using the circuit as in Fig. 1 on the same insulator with the same value of voltage applied, it was necessary to make a 10 per cent potentiometer connection for the noise meter on resistance R. The output for the insulator at that voltage was, therefore, 50 microvolts at radio frequency and represents the starting value of interference for the particular arrangement described. In Fig. 4 is illustrated the output for insulators with and without treatments. This is on a larger scale that permits more accurate selection of output values for respective voltages.

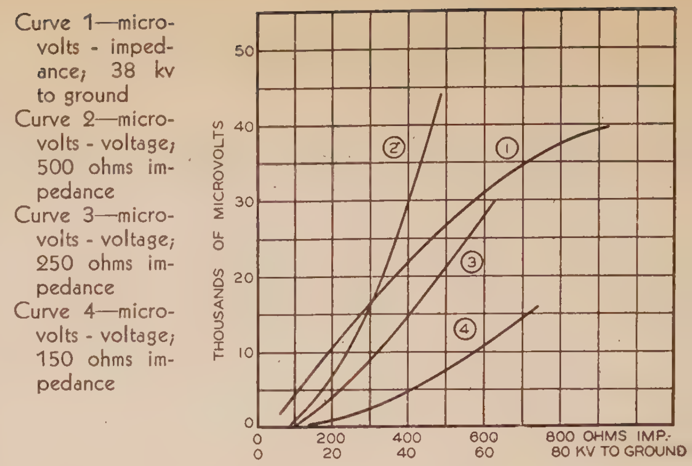


Fig. 2. Radio frequency output for a 66-kv pin type insulator with grounded pin

Metallic Glaze Treatment

Reference was made to the development of treatments for improving the radio influence characteristics of insulators. Table I and Fig. 4 give data showing such improvement for a treated pin type insulator. The improvement is obtained by eliminating the ionization surrounding the conductor and tie wire areas and any discharge in the pin hole. This is accomplished by the use of a metallic glaze over the crown area that provides a low resistance metal to metal contact between the conductor and tie wire and the insulator, with a metal thimble cemented into the pin hole.

A number of methods for eliminating or reducing the ionization and other distress over the crown area were proposed and tried by the various investigators in their early work. In addition to several types of metallic glazes, other promising features were modifications in shape to control the discharge, a metal cap cemented to the crown for the attachment of the conductor and tie wire, and the filling of the wire grooves with compounds to exclude the air. All of these gave varying degrees of improvement; all possess some disadvantages.

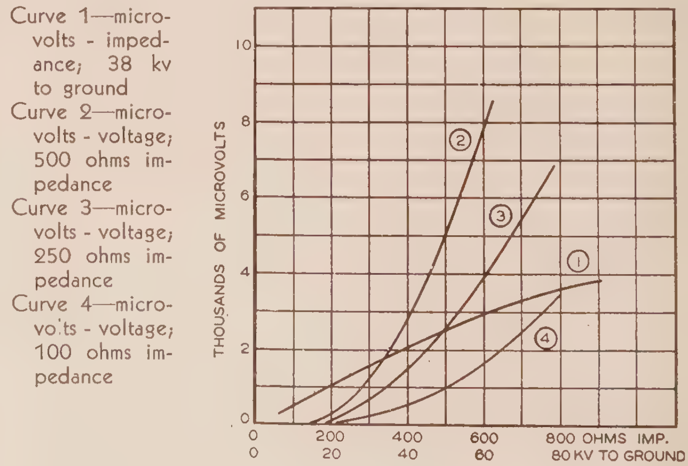


Fig. 3. Radio frequency output for a 66-kv pin type insulator with ungrounded pin

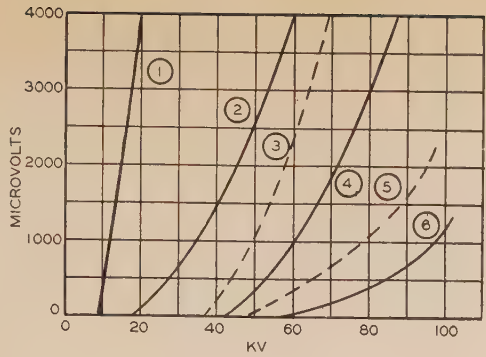


Fig. 4. Radio frequency output; regular and treated 66-kv pin type insulators

Curve 1—regular insulator; grounded pin
Curve 2—regular insulator; ungrounded pin
Curve 3—asphalt treated insulator; grounded pin
Curve 4—copper oxide glaze treated insulator; ungrounded pin
Curve 5—asphalt treated insulator; grounded pin
Curve 6—copper oxide glaze treated insulator; ungrounded pin

The first metallic glazes transferred the potential and the corona discharge from the wire grooves to the periphery of the conducting coating. This difficulty has been overcome with a later development in the art and science of a metallic glaze. The first metallic glazes were applied to the regular insulator glaze after the firing of the porcelain was completed. The later development uses a copper oxide glaze to replace the regular silicate glaze on the insulator. The copper oxide glaze comprises a large percentage of copper oxide in a composition that is applied and matured in the regular manufacturing processes. This special glaze is applied in commercial production to the upper side of the top part of the insulator, the other surfaces having the regular silicate glaze coating. After the porcelain is fired the copper oxide glaze is reduced to metallic copper over the area surrounding the wire grooves. This metallic copper coating which is molecularly attached to the porcelain is developed by a chemical reaction between zinc and a solvent in contact with the oxide glaze. This developing agent can be confined to any local area so that only the desired surface is changed to the metallic state.

The edge of the developed metallic coating has an inherent graded conductivity from the fully conducting area to the undeveloped high resistance area. This is effective in damping out the edge discharge difficulty of the early metallic glazes. The developed copper area is given a tinned coating to protect it against oxidation and mechanical abrasion. Fig. 5 is a photograph of the copper oxide treated insulator with the tinned coating.

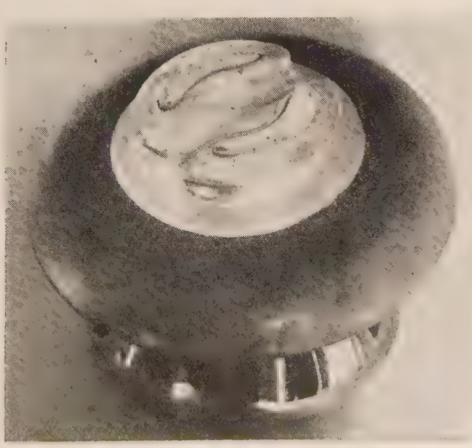


Fig. 5. Insulator with copper oxide glaze treatment

The data given in the tables for the treated insulators were obtained on insulators with the copper oxide glaze treatment on the top of the head and a thimble cemented into the pin hole. Successive tests show no change in this performance over a period of 2 years of accelerated life test, with 170 per cent of normal potential applied.

Curves 4 and 6, Fig. 4, show the improvement obtained with the copper oxide glaze treatment on a 66-kv insulator. Comparative results are obtained with the treatment on insulators of other ratings.

The values of voltage at which the 50 microvolt signal is produced for pin type insulators of standard size and rating, with and without treatment, are given in Table II.

Table II—Kilovolt to Ground to Produce 50 Microvolts at Radio Frequency in a Circuit of 250 Ohms Impedance

Size of Insulator: Kv	Size of Insulator: Diam. In.	Condition	Grounded Pin (Kv)	Ungrounded Pin (Kv)
15	7 1/2	Regular	9	18
		Treated	22	50
23 1/2	9	Regular	9	19
		Treated	22	54
34 1/2	10	Regular	10	21
		Treated	28	56
46	12	Regular	10	21
		Treated	40	56
66	13 1/2	Regular	9	18
		Treated	41	58

Apparatus and Suspension Type Insulators

The characteristics of apparatus insulators, such as are used in switches and bus structure, and of suspension insulators also are of interest.

The apparatus insulator, Fig. 6, with the metal parts cemented to the crown and in the pin hole presents a combination that led to the use of the metal cap as one type of improvement for the pin type insulator. The cap furnishes a low resistance metal to metal contact with energized parts connected to it. The cement between the cap and the porcelain excludes the air between them, thus reducing or eliminating any ionization over that area. This results in substantial improvement in the signal level as indicated in Fig. 7, which shows that the characteristics for a 66-kv pin type insulator and for the same insulator in the apparatus type assembly. The improvement is limited by the ionization in the gap between the edge of the cap and the porcelain that is provided in the usual assembly to permit differential expansion without damage to the porcelain. The copper oxide glaze treatment over the crown area eliminates the potential and corona across this gap and gives further improvement.

Suspension insulators have similar characteristics but much lower output over the normal voltage range. In Fig. 8 is illustrated their performance in

string lengths of 4, 8, 12, and 18 units. These were the so-called $10 \times 5^3/_4$ standard rating. At critical voltages the output for the longer string lengths rises abruptly as indicated by the curves. A circuit similar to Fig. 1, but with a high voltage transformer set-up was used for the tests on suspension insulators. An indication of the audible effect of such performance was obtained with the receiving instrument[3] on the ground 23 ft below and 15 ft to the side of the test bus. The voltages at which interference was first detected with an earphone set are as follows:

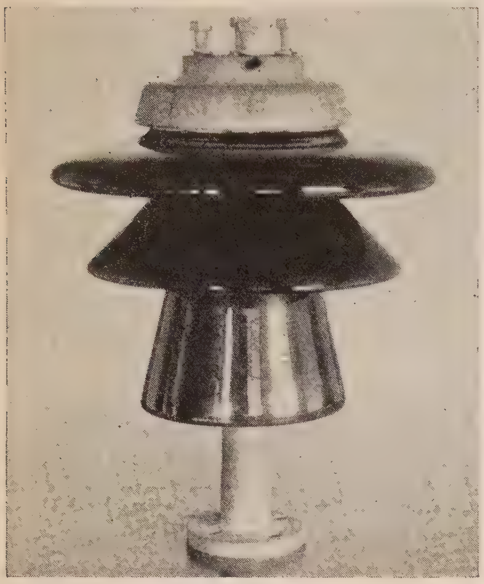
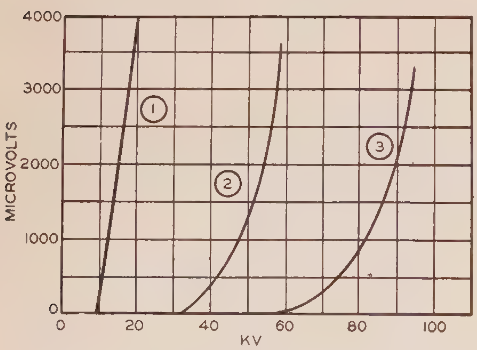


Fig. 6 Apparatus type insulator



Curve 1—regular pin type design; grounded pin
Curve 2—regular apparatus design; grounded pin
Curve 3—copper oxide glaze treated apparatus design; grounded pin

Fig. 7. Radio frequency output for apparatus type insulator; 250 ohms circuit impedance

Units in String	Kv	Equivalent 3-phase Voltage, Kv
4	85	145
8	140	240
12	180	310
18	195	335

These voltages correspond to the critical values on the output curves. They show a wide margin, especially at the shorter string lengths, over present normal operating voltages. For this reason treatment to improve the interference characteristics of suspension insulators does not now appear to be warranted.

Treatment of Old Insulators

The copper oxide glaze treatment can be furnished only on newly manufactured insulators. Its advantages of permanence and superior performance are, therefore, not applicable to insulators now in service. A treatment that can be applied to insulators now in service is the filling of the wire grooves with a compound to exclude the air. At best, this treatment can be considered as a temporary expedient because of the limited life of the filling materials that will serve for this purpose. Asphalt compounds offer the best known weathering properties of such a material. A compound in semi-paste form, as asphalt emulsion, can be applied more easily than a paint or melted type of material. In Fig. 9 is shown an insulator with the asphalt emulsion treatment. Curves 3 and 5, Fig. 4, show the radio influence characteristics of a 66-kv insulator with this treatment over the crown and a thimble in the pin hole, with grounded and ungrounded pin.

Fig. 8. Radio frequency output for suspension type insulators; 600 ohms circuit impedance

Curves show respectively result for 4, 8, 12, and 18 units

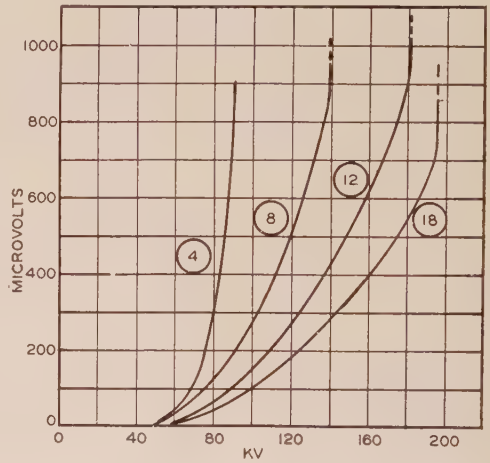


Fig. 9. Standard pin type insulator with asphalt emulsion treatment

The asphalt emulsion treatment can be applied to

the gap between the cap and the porcelain on apparatus type insulators with improved results.

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Voltage Regulation and Load Control

Some of the problems involved in supplying electric power to the business sections of large metropolitan areas are dealt with in this article which describes the development and operation of new methods of voltage regulation and load control by means of which improved conditions are being obtained on the distribution system in New York City.

By
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THE A-C distribution system in New York City is mainly supplied by feeders direct from the generating station buses, the necessary transformation to reduce the voltage to the network potential being made by network transformer installations located in street manholes and in vaults in buildings. This major supply is supplemented in certain areas by substation feeders of lower voltage which were formerly used for radial service.

In the early stages of the development of the network it was considered advisable to have feeders in each network area from as many sources of supply as practicable. As a result, many network areas exist where feeders from two generating stations are paralleled, or "intermeshed" on the secondary side of their respective network transformers. In the case of individual generating stations it has also been found desirable in the interest of improved reliability and reduced circuit breaker duty to operate the station buses in two or more distinct sections. Feeders emanating from these bus sections likewise are intermeshed mutually on the secondary network as described above. The present major connections of the 60-cycle system are illustrated in Fig. 1.

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VOLTAGE CONTROL

As the network system progressed the high cost of using feeder regulators for controlling the network voltage led to the idea of obtaining the necessary regulation by varying the voltage on the generating station buses and thus a closer relationship between the generating stations and the distribution system was first established. As a result of calculations and various experiments there was finally established the practice of varying the bus voltage in accordance with a schedule which was determined as a function of the total system load. This plan largely eliminated the difficulties inherent in any scheme based on varying the voltage according to a definite time schedule, this method being subject to criticism on account of the unpredictable variations in the daily load curve. It will be obvious that controlling the voltage in this manner requires very accurate voltmeters at the generating stations if good results are to be obtained. The present voltmeters at Hell Gate station are considered to be somewhat deficient in this respect since their accuracy is only plus or minus 1 per cent so that even if the voltage schedule is strictly adhered to, the network voltage may vary as much as plus or minus 1.2 volts in addition to the normal variation associated with the distribution system potential drop. While this may seem slight nevertheless when it is the aim to maintain the voltage delivered at the consumers services within a band of 8 volts it is a serious handicap to lose at the outset, due to inaccuracy of voltmeters, about 2.5 volts. It is now proposed to install at Hell Gate combined indicating and recording voltmeters of the type shown in Fig. 2. These equipments which are manufactured by the Leeds and Northrup Company are accurate to plus or minus 50 volts based on a 2,000-volt range of scale, so that in controlling a nominal voltage of 13,800 volts the accuracy is better than plus or minus 0.5 per cent. In providing voltmeters for use in supervising such an important function, of course, it is equally necessary that the instruments be of a type which have a large scale so that they can be read closely.

With the careful coöperation of the generating station operators the method of regulation by control of bus voltage has given excellent results on the whole. There are, however, certain areas having load characteristics differing substantially from the major part of the system where the scheme of bus regulation leaves something to be desired. In the southern part of Manhattan Island for example, the load is largely for office buildings and after 5 p.m. it drops to a low amount, whereas the load on the major part of the system continues near its peak for some time. Under these conditions it is obvious that

ideal results cannot be obtained by bus regulation as the voltage will necessarily be higher in the lightly loaded area than elsewhere on the system. It may be necessary to supply areas of this type with feeders having individual regulators or possibly from a bus which does not supply any other load and so can be regulated independently of the rest of the system.

Coöperation in the design and operation of the generating systems has been of definite value also in the problem of controlling the division of load on transformers connecting to feeders which are derived from different stations or from independent bus sections in the same station and intermeshed at the network. Under these conditions if one supply bus happens to be appreciably leading or lagging in phase position with respect to the other sources of supply a corresponding increase or decrease in the loading of the transformer banks connecting to the feeders will occur. As an example, consider the network in lower Manhattan which is fed jointly by Hell Gate and Hudson Avenue generating stations. At the time of peak load and with zero phase displacement between

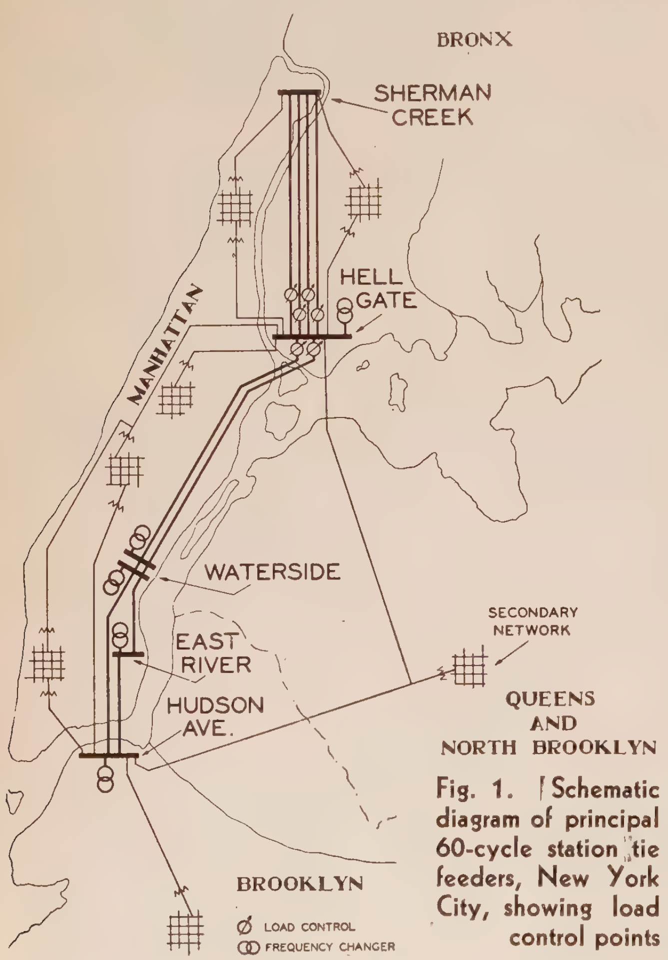


Fig. 1. Schematic diagram of principal 60-cycle station tie feeders, New York City, showing load control points

the station buses, the average transformer on a Hell Gate feeder is loaded to 47 per cent of its kva rating and at 92 per cent power factor, but some transformers are 80 per cent and others only 20 per cent loaded. Likewise the average transformer on a Hudson Avenue feeder is loaded to 50 per cent of its kva rating and at 89 per cent power factor, but some transformers on this feeder are loaded also 80 and 20 per cent, respectively. With Hell Gate leading Hudson Avenue by 3 deg the 80 per cent loaded transformer on the Hell Gate feeder would be 100 per cent loaded and the 20 per cent loaded transformer on the Hudson Avenue feeder would be carrying a load equal to 6 per cent of its kva rating. On the

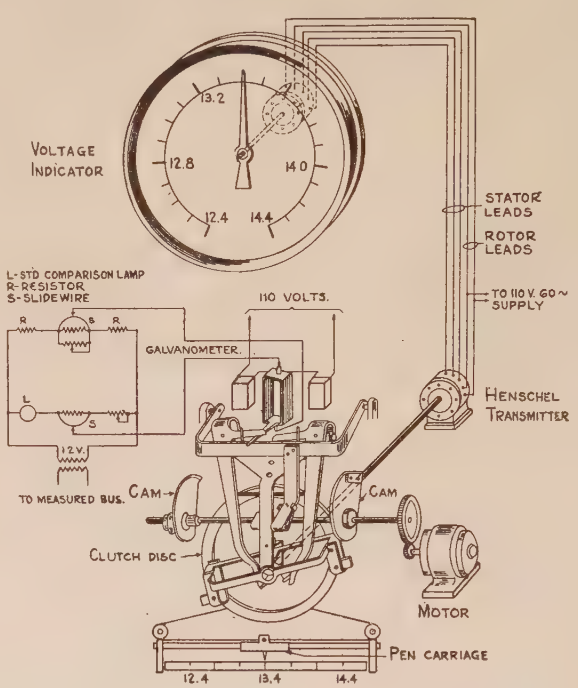


Fig. 2. Bus voltage recorder and remote indicator proposed for installation at Hell Gate Station

other hand, if Hudson Avenue leads Hell Gate by 3 deg, the 80 per cent loaded transformer on the Hudson Avenue feeder would be 90 per cent loaded, but the 20 per cent loaded transformer on the Hell Gate feeder would be feeding back toward Hell Gate a kw load equal to 2 per cent of the transformer rating. The network protector associated with this transformer would automatically open if the relays were given a sensitive reverse energy setting.

If angular displacements of the order of 3 degrees were introduced during off-peak periods, inevitably a large number of sensitive protectors would open and remain open well into the peak load period, in some cases even remaining open regardless of load period until the phase-angle condition was corrected or until the protector was closed by hand. This operating difficulty obviously could not be attributed to any deficiency on the part of the operators who had no means of knowing the relative phase position of the several bus sections. Evidently an instrument which would give this information, was needed both for the guidance of the station operators and for the benefit of the engineers concerned with the layout of the distribution system.

Phase Measuring Equipment

In discussing the development of phase-measuring equipment we shall first consider its application to

the measurement of phase displacement between bus sections located in the same station. Fig. 3 showing the present normal operating connections at Hell Gate is illustrative of this case. In casting about for a suitable measuring equipment the first thought was to use an instrument of the electrodynamometer type. It was found soon, however, that ordinary instruments of this type were not sufficiently sensitive to small angular differences and even with improved instruments an accuracy of not better than plus or minus 30 min was the best that could be expected. Moreover, all of the available instruments were of the indicating type whereas it was felt that a recording equipment was much more suitable since it permits a day-to-day study of changing conditions which periodic and nonsimultaneous readings do not afford. Eventually as the result of development work which was carried out in the laboratories of the New York Edison Company in

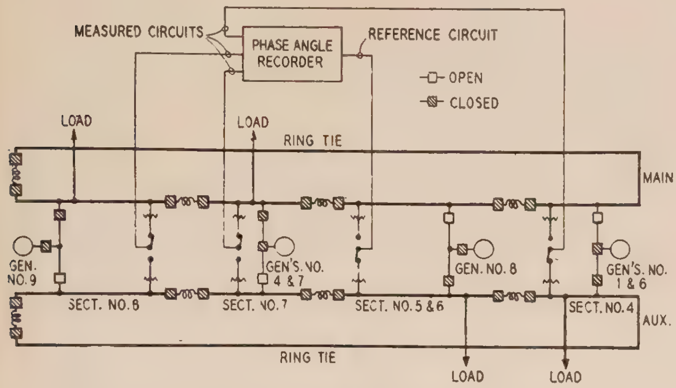


Fig. 3. Present normal operating connections at Hell Gate

coöperation with the Leeds and Northrup Company, who were interested in the problem from the manufacturing standpoint, a suitable recorder was constructed. The instrument is basically a form of a-c potentiometer and employs a null method of measuring the angle between two sources. It is a modification of the potential transformer testing set manufactured by Leeds and Northrup of which the fundamental principles were described by Dr. F. B. Silsbee in his paper entitled "A Method for Testing Current Transformers" (U. S. Bureau of Standards Scientific Paper 309, 1917).

The features of the potential transformer testing set necessary for measurement of phase difference were combined with the Leeds and Northrup Micromax recorder forming an instrument of which the electrical and physical features are illustrated by Fig. 4. The slide wires S_1, S_2, and S_3 were mounted on the same shaft and by their movement cause the relative values of capacity and resistance to change until zero deflection of the galvanometer is obtained. The recording pen is belted to the slide wire and records the position of the slide wires when the galvanometer reaches a balance. The range was extended by using suitable resistors and condensers to give a record of phase difference of from plus 5 to minus 5 deg. The resistor R_5 and condenser C are used to provide damping and stability of the galvanometer.

The instrument will measure the phase displacement between constant potentials to an accuracy of plus or minus 3 min and variations in the potential of 10 per cent only decrease the accuracy to plus or minus 9 min. The over-all accuracy of the record, however, also depends upon the care which is taken to compensate for the phase-angle error of the potential transformers to which the instrument is connected. Ordinarily where the burdens are small it should be possible to connect the instrument to existing transformers without appreciable error. However, the burdens should not be subject to alternate connection and disconnection. Potential transformers connected Y–Y may be used if all the burden is connected phase to neutral on the transformer used for phase-angle measurements. Care must be taken however, to prevent stray secondary currents from entering the circuit. The high lagging burden of the galvanometer field is compensated by a shunt condenser.

The protective relay shown in Fig. 4 is used to avoid the possibility of unintentionally keeping a bus section alive by reason of a back feed through the potential transformers which have their secondary circuits interconnected through the instrument. The isolating transformers are used to prevent circulating current due to differences in potential between the transformer secondary grounds. The selector switch of the multiple point unit is covered with a bakelite cap to prevent the accidental bridging of contacts.

The connections of the instrument as installed at Hell Gate station were shown in Fig. 3. It may be noted that the device measures the phase displace-

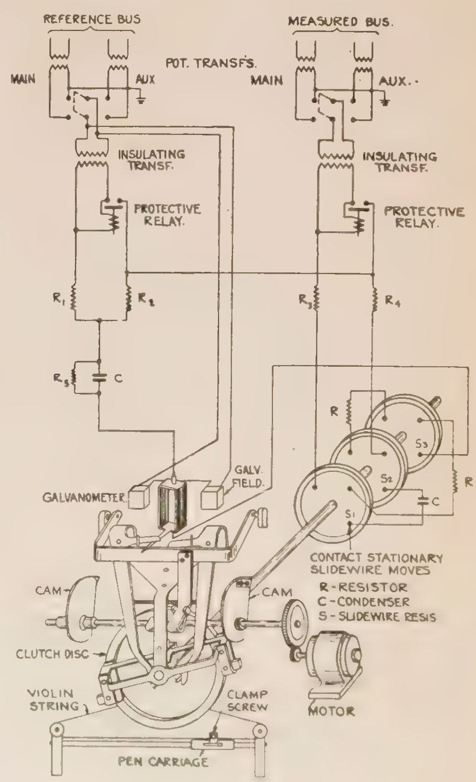


Fig. 4. Electrical and physical connections of a phase angle recorder, combining features of potential transformer testing set and "Micromax" recorder

ment between one bus section which is arbitrarily chosen as the master or reference bus and 3 other bus sections. By means of selector switches it is possible to obtain phase measurements of the remaining bus sections, if desired, although this is ordinarily unnecessary. Fig. 6 shows the phase conditions immediately after installing the instrument, before any corrective steps had been taken as compared to the conditions after loading and operating practice had

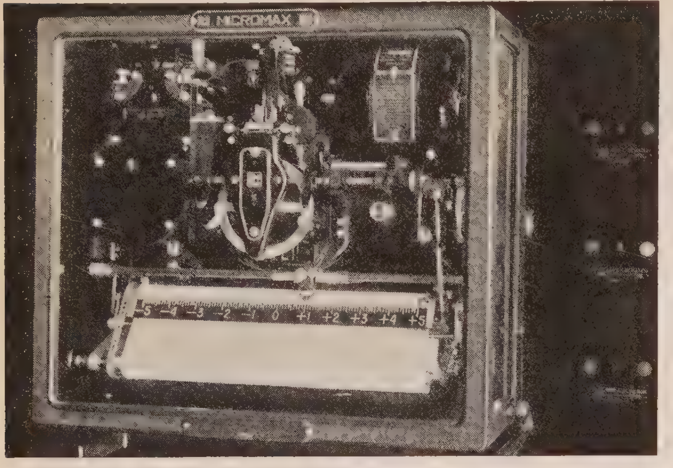


Fig. 5. Phase-angle recorder used at Hell Gate

been readjusted to minimize as far as practicable phase displacements.

We shall turn now to the case where feeders from separate generating stations are intermeshed at the network. Referring to the diagram of system connections (Fig. 1) attention is called to the arrangement of the direct ties between Hell Gate and Hudson Avenue stations which are tapped as shown in order to connect with the frequency changers at the Waterside and East River stations. The transfer of load between Hell Gate and Hudson Avenue over these direct ties without a phase displacement between the two stations in the absence of load control equipment would be impossible. In order to overcome this difficulty load control transformers were installed in the ties at Hell Gate making it possible to transfer load in either direction over the ties up to their rated capacity without phase displacement between the station buses. The connections of the transformers are shown schematically by Fig. 7 from which it will be noted that the transformers introduce a series voltage displaced by 120 deg from the line to neutral voltage. With this arrangement an advance in phase when introduced by the series windings is accompanied by an increase in voltage and this operates to keep the power factor on the ties at a slightly lagging value. This is to be desired since it is well to have the station which is sending energy out over the ties also take on some additional lagging reactive kva in order that the receiving station may not find itself in the position of being relieved of a substantial amount of energy without any corresponding relief in the amount of lagging reactive kva which it must supply.

Measurement of Phase Displacement Between Generating Stations

The mere installation of load control transformers at Hell Gate, however, was not a complete solution to the problem for although it made possible the transferring of power over the ties without requiring phase displacement between the buses of the two stations it still left the operators without any way of knowing whether they were obtaining the desired load transfer from a proper adjustment of the load control transformers or whether the load transfer was being obtained in part by an unwanted phase displacement between the stations. A first attempt to solve this difficulty consisted of providing the operators with a somewhat complicated set of curves from which the correct setting of the tap changers could be determined in terms of the load on the ties and the loading of the frequency changers which were connected to the ties. Since the various loadings were all widely variable it was soon found that the collection of simultaneous readings of the load on the ties and on the frequency changers together with the application of the curves to determine the tap settings was such a cumbersome process and required so much time that there were large phase displacements before the proper correction in tap settings could be made. Here again the indicated solution was a direct measurement of the phase displacement between the buses of the two stations. Accordingly attention was turned to the application of the phase-measuring equipment, of which the

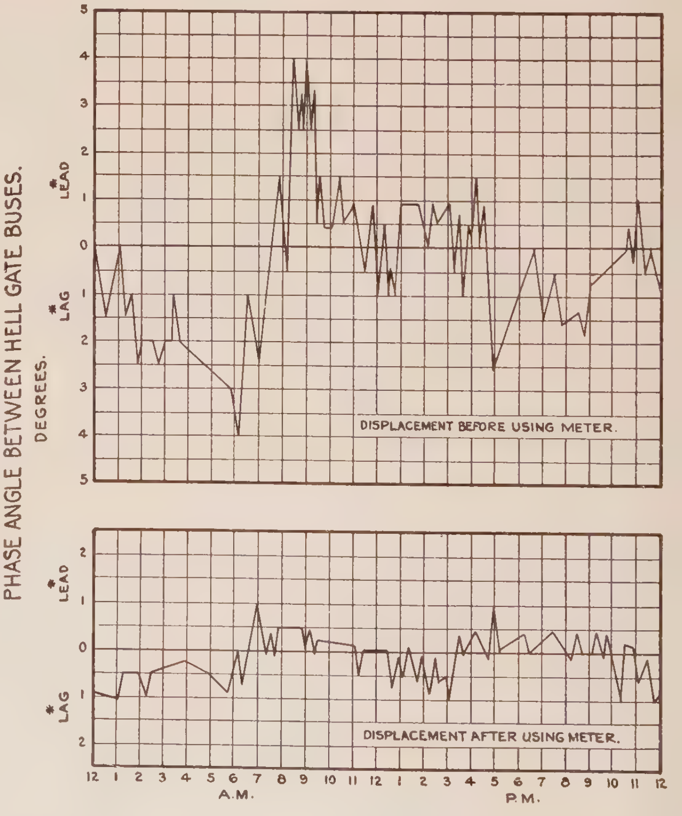


Fig. 6. Comparative phase angle displacement between Hell Gate buses before and after using phase angle meter

development has already been described, for use in connection with a pilot wire in order to determine the phase displacement between two comparatively remote potentials. It was known that the pilot wire impedance would necessarily be large and would be variable to a considerable extent due to temperature changes so that some form of compensation would be required. One solution to the compensation problem which was suggested was to use one instrument at each end of a symmetrical line as shown in Fig. 8. Under this set-up the effect of the pilot wire impedance is cancelled.

This may be shown by the following simple equations:

θ_x = true phase angle between stations.
ϕ = phase displacement caused by the pilot wire.
θ_1 = reading taken at station *A*.
θ_2 = reading taken at station *B*.

Then $\theta_1 = \phi + \theta_x$

$\theta_2 = \phi - \theta_x$

Subtracting, $\theta_x = \dfrac{\theta_1 - \theta_2}{2}$

The success of this method depends on the lines being symmetrical, that is, the lines may be made up of different wire sizes but the electrical constants looking into the line in either direction from its midpoint must be the same. If not, the angular displacement in one direction will be different from the displacement in the other direction because of the distribution of the capacity and resistance. Since commercially available telephone circuits are rarely symmetrical as herein defined and because of the expense of the additional instrument, further tests were made to determine the limits of accuracy and

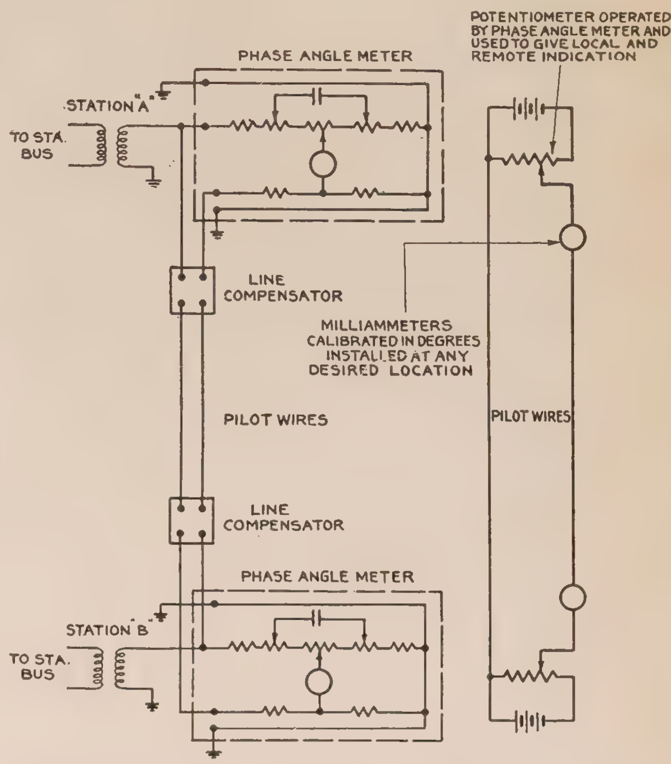
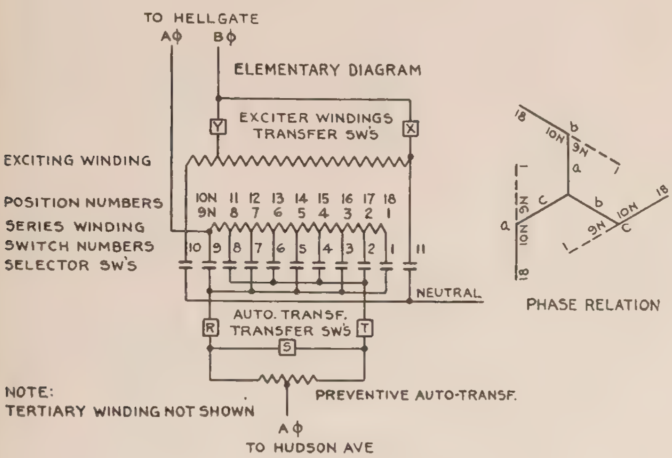


Fig. 8. Null method of remote measurement of phase angle



SEQUENCE OF OPERATION

BUCK — BOOST

POSITION	1		2		3		4		5		9N	TEST	10N		11		12	16		17		18
SWITCH #1	O	O																			O	O
" 2		O	O	O															O	O	O	
" 3				O	O	O												O	O			
" 4						O	O	O														
" 5								O	O													
" 6																						
" 7																O	O					
" 8										O				O	O	O						
" 9										O	O	O	O	O								
" 10	O	O	O	O	O	O	O	O	O	O	O											
" 11													O	O	O	O	O	O	O	O	O	O
"																						
" R	O	O		O	O	O		O	O	O	O	O	O	O		O	O	O	O		O	O
" T		O	O	O		O	O	O		O				O	O	O			O	O	O	
" S	O		O		O		O		O		O	O	O		O		O	O		O		O
" X	O	O	O	O	O	O	O	O	O	O	O											
" Y													O	O	O	O	O	O	O	O	O	O

O- CLOSED POSITION OF SWITCH

Fig. 7. Load ratio control transformer and sequence chart, Hell Gate station

the practicability of using a single instrument and a compensator for the angle introduced by the pilot wire. Tests conducted in coöperation with the New York Telephone Company and the American Telephone and Telegraph Company, determined that, with the exception of special routing through the control office and the addition of compensating equipment at the terminus, commercial telephone circuits could be used as pilot wires. Fig. 9 shows the circuit used for a single-phase measuring instrument, including compensation for angular displacement in the pilot wire between zero and 45 deg leading. Using such a circuit and a pilot wire looped back to the same point it was found that an error of less than 1 deg was introduced. The compensator is designed so that a constant potential may be obtained from the output terminals of the instrument over a wide range of angular compensation.

Temperature changes affect the impedance and hence the phase angle of the pilot wire, but these changes are gradual. To detect these changes and obtain constant supervision of the pilot wire (detect open circuits, etc.), the voltmeter shown in the diagram of connections, Fig. 9, is used. This voltmeter is a d-c milliammeter used with a copper oxide rectifier and a resistance of 2,000 ohms per volt and hence does not require enough current to affect the accuracy of the indication. The instrument is

first calibrated by checking against two voltages of known displacement and then the circuit is calibrated at zero by adjusting the generators in each station until minimum current passes through a direct circuit between the remote buses.

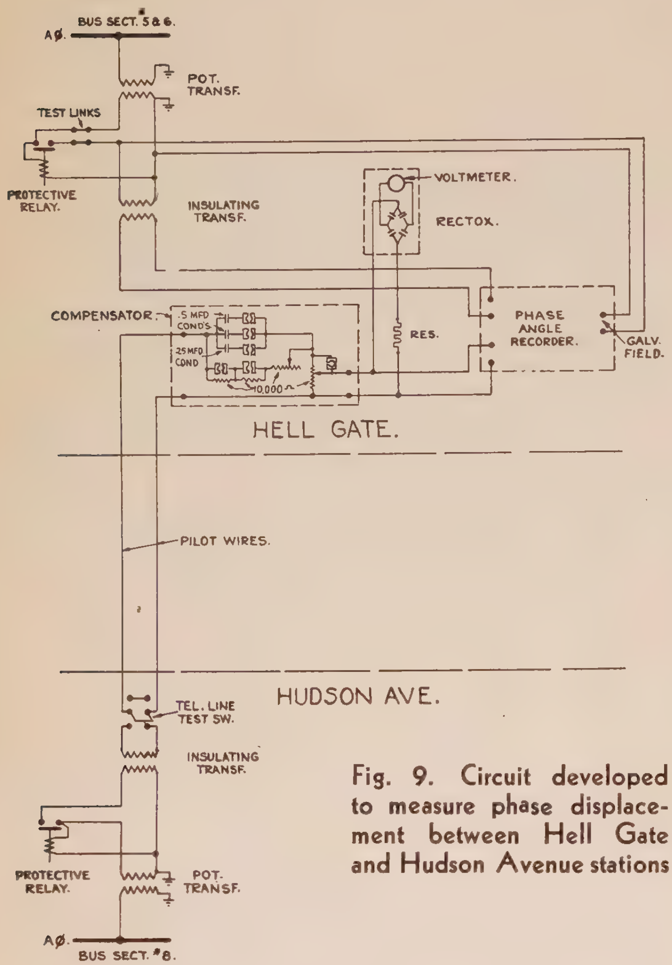


Fig. 9. Circuit developed to measure phase displacement between Hell Gate and Hudson Avenue stations

The comparative conditions as to phase displacement when operating the load control transformers in accordance with the method previously described and when controlling the tap changers by direct observation of the phase meter are illustrated by Fig. 10. Under normal operating conditions it is now practical to keep the angular displacement within plus or minus 30 minutes. It is to be noted that at Hell Gate the phase meter is connected to the bus section which is used as a reference bus for the local phase meter.

Referring again to the diagram of system connections (Fig. 1) it will be seen that the same operating problem exists in the case of the Hell Gate and Sherman Creek stations as in that of Hell Gate and Hudson Avenue. However, the problem of keeping the buses of the two stations in phase in this instance was solved in a different manner.

Using Regulators for Phase Control

The availability of several sets of induction regulators at Hell Gate led to the thought of using them to provide the desired load control in the direct ties between Hell Gate and Sherman Creek. These regulators were single phase and had formerly been used in pairs with the open delta connection as feeder voltage regulators. Reconnecting the regulators as shown by Fig 11, it was possible to obtain an advance or retardation in phase by changing the position of the regulators without any distortion in the 3-phase voltage although a change in the position of the neutral was involved. The neutral shift, however, occasioned no difficulty since it was possible to operate the Sherman Creek station with the

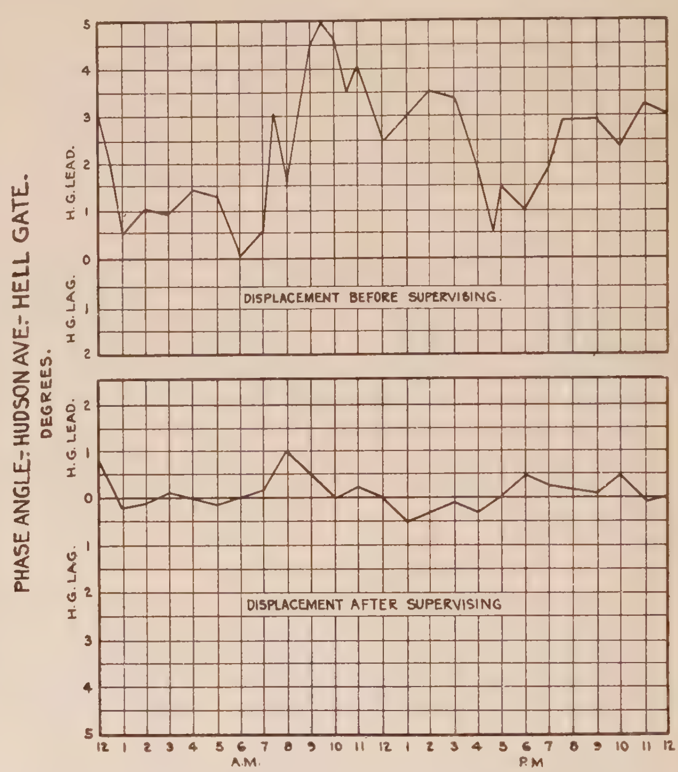


Fig. 10. Comparative phase angle displacement between Hell Gate and Hudson Avenue stations before and after using phase angle meter

neutral ungrounded, relying on the ties for supplying ground current. Since the direct ties between the two stations in this instance had no load tapped from them between the two stations it would have been a simple matter to make a chart from which the proper regulator settings could have been determined in terms of the load on the ties. Nevertheless manual control of the regulators in this manner was not considered a very satisfactory solution as it required a great deal of time and careful supervision by the operators if good results were to be obtained. Accordingly, studies were made of the practicability of applying automatic control to the regulators so that they would automatically change their position as required by the loading on the ties. This was finally accomplished by connecting the contact-making voltmeter and line drop compensator mechanisms, with which the regulators were already provided, in the manner shown by Fig. 11. It is

believed that this diagram of operating connections is largely self-explanatory except that the purpose of the transformer which steps down the base potential applied to the contact-making voltmeters may not be clear. It was the purpose of this transformer to reduce the basic potential to a value low enough so that the variations in it due to the daily variation of bus potential, for the purpose of controlling the network voltage, would be insignificant by comparison with the voltage variations set up in the line drop compensator as a function of the load on the ties. The position of the regulators, therefore, could be regarded as being substantially proportional to the load on the ties.

It can easily be shown that the phase control provided by the regulators is such that energy is transferred over the ties at substantially unity power factor. With energy normally being fed toward Sherman Creek and operation at that station

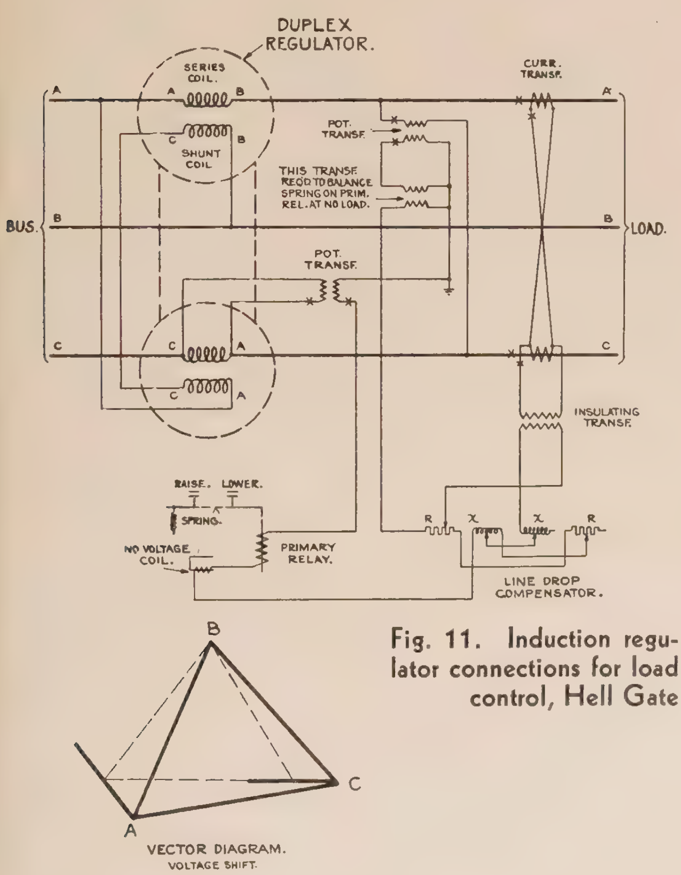


Fig. 11. Induction regulator connections for load control, Hell Gate

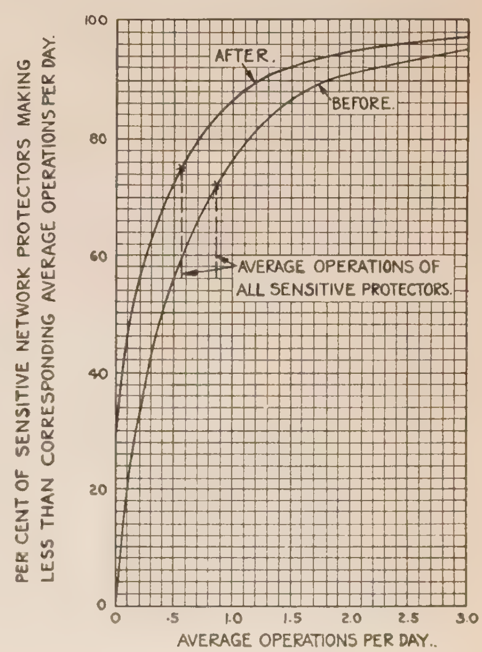
at a reduced basis, except under emergency conditions, it became a problem as to how the necessary reactive kva was to be supplied, the situation having reached a point such that generators required on the bus to carry the energy load were not of sufficient capacity to handle the reactive load. This was satisfactorily taken care of by uncoupling two of the generators from their turbines and operating them as synchronous condensers. A separate turbo-generator unit which applied gradually increasing voltage and speed was used to start these uncoupled generators and bring them up to synchronous speed. Although this method of starting is cumbersome it is satisfactory enough where as in this case, it is not necessary to do it often.

Better Network Protector Operations

After the installation of phase-angle indication, the network protector operations showed a marked improvement as indicated by Fig. 12. This record gives the experience with sensitive network protectors in Manhattan which represent 75 per cent of all network protectors installed in the Manhattan district. These protectors and their associated distribution transformers are fed from the various bus sections of three generating stations, therefore their operation is representative and provides a definite means of comparing system operations before and after the installation of phase-angle indications. The average operations per protector per day were reduced from 0.89 to 0.57, a 36 per cent improvement over the earlier condition. Furthermore, the operations in excess of the average per day are confined to 25 per cent of all sensitive protectors.

It is expected that many protectors now insensitive because of feeder phase-angle relations previously experienced may now be made sensitive without increasing the average operations for all sensitive protectors, and changes along these lines are now proceeding. The work of the engineers concerned with the distribution system has also been facilitated for it is now possible to tell with a much greater

Fig. 12. Network protector operations before and after installation of phase angle recorders at generating stations



degree of accuracy the true distribution load carried by the network transformer installation, since measurements of transformer loading are largely uncomplicated by artificial circulating load due to improper phase conditions within the stations. Therefore additional network transformer installations can be placed on a more rational and economical basis.

Encouraging Initiative in the Engineering Student

Engineering education today is being examined from within as well as from without, with the object of adapting it to meet more adequately the changing demands of a profession broad and diverse although relatively young. With no precedent or past experience to serve as a guide, engineering education necessarily has developed by its own efforts through trial and experiment. This paper describes the educational methods adopted at Harvard Engineering School in an effort to solve the problem of training engineering graduates for the varied responsibilities that they may be called upon to assume.

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WE ALL ARE familiar with many specific criticisms of engineering graduates; they are unable to express themselves in good English; their training in the fundamentals is deficient; they are failing in the broad knowledge of human qualities and in economics; they are narrow technicians; their technical training is shallow and superficial; they are lacking in initiative and resourcefulness, and so on. The commendable qualities are seldom mentioned. However, these criticisms should be examined carefully with the object of improving educational methods.

Although it has been generally recognized for some time that lack of initiative and resourcefulness is an existing defect in engineering graduates, there have been few suggestions or recommendations for correcting it. The numerous discussions appearing in both technical and educational publications indicate the wide and active interest taken in engineering education.[1]

In a recent paper, Dean Dyche of the University of Pittsburgh and R. E. Hellmund of the Westinghouse company[2] discussed in some detail the lack of initiative and resourcefulness in engineering graduates and offer as a remedy the Pitt-Westinghouse graduate program. But this program is adapted to graduates only and is limited to very few schools which are located near a large electrical industry.

In its extensive report on engineering education, the Society for the Promotion of Engineering Education board of investigation and coördination[3] devotes almost no space at all to this question. One short paragraph on p. 130 is as follows:

> Motivation.—One of the marked values of the unified program entered directly from the secondary schools is that it capitalizes the student's natural motivation. To keep the student longer away from studies which bear on his life purposes tends to prolong a juvenile attitude toward education at a time when he needs to learn the method of intensive directed effort.

A large part of the report[3] is devoted to studies of the curriculum, with special reference to the percentages for each subject. The amount of thought and discussion given to balancing the curriculum seems to imply that improvement in engineering education lies almost entirely in that direction. Standardization of the curriculum is disadvantageous to the student's development as an engineer. It is not possible to say that the particular group of subjects appearing on a program of study is the arrangement which on the whole develops individually the best engineers. The available data do not justify any high precision in selecting the proportions of the curriculum which should be allocated to each of a number of selected subjects. The greatest fallacy is the assumption that a single curriculum in a particular field of engineering best meets the needs of all students. No 2 students have the same interests, aptitudes, or abilities, and the selection of subjects of study for each should be determined by the requirements of the individual. To be sure, in most programs some choice is offered but, according to the S.P.E.E. report,[3] the proportion of electives in engineering-school programs is, with few exceptions, very small.

The committee on professional training of the Engineers' Council for Professional Development,[4] of which Col. R. I. Rees is chairman, is taking measures to assist the young engineer in self-analysis and self-development. It would seem desirable that during the period of formal education the engineering schools should also take measures to assist students in these same directions. The engineering schools have a position of advantage for doing this, as they meet students at an age when these young men are forming their habits, and thus the only changes required are some modifications in the methods of instruction.

Faults of Prearranged Curricula

Setting up fixed educational requirements, rather than adapting these to the characteristics of the individual, has the effect of discouraging and suppressing initiative and resourcefulness in the student. This is true not only in the engineering school, but throughout the student's educational career. From elementary school days the engineering student is accustomed to having his educational career planned for him to the smallest detail. The program of study, allocation of time, and even the method of

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1. Numbers refer to bibliographic references at end of paper.

holding a pencil and of writing have been carefully planned and standardized, irrespective of individual ability and talent. Although in the better secondary schools a diversity of subjects is offered, students preparing for college have little option. By their entrance requirements the colleges in large measure determine the program of study and the student, in soldierly fashion, follows the program, usually faithfully, but also blindly. He does not know why such a group of studies prepares him for college better than some other group that perhaps might arouse in him a much keener interest.

In the usual engineering school, after selecting his general field of study, the student finds the curriculum all arranged for him and, with minor options, is identical for all students in the same field. He does not know why this prescribed course of study best fits him and his fellow students for their chosen profession. He probably gives little thought to this particular question, but he may unconsciously assume the plan to be due to the wisdom of some one higher up who should know. He does know that if he completes with success the schedule of individual courses prescribed, he will be awarded the degree and that he should then be fitted to begin professional work. He also finds in the classroom and in the laboratory a definite schedule arranged for him. Formal lectures and definite problem assignments follow each other leading to the final examination of the term. In the laboratory he is assigned from week to week definite tests on certain pieces of apparatus. In many cases the laboratory procedure and the necessary instruments are prescribed for him and he finds the apparatus already set up. To be sure, the preliminary report method if used does require some planning on the part of the student, but the effect of this alone develops little if any initiative.

Educational Plan

Feeling that the rigid curriculum and the usual methods for teaching engineering students was confining them to an educational strait-jacket, the faculty of the Harvard Engineering School under the leadership of Dean H. E. Clifford studied the problem carefully and decided that placing a large measure of responsibility on the student would tend to develop self-reliance, the habit of planning his future, and initiative as well. Also, history has shown that, as a rule, men are developed in proportion to the responsibility placed upon them.

Therefore, the following policies were adopted and have been followed for 2 years.

1. The curriculum was to be elective, not fixed. The student, even as a freshman, was to plan his course of study and arrange his entire program.

2. The reading period was adopted in those courses in which the student has acquired sufficient background to continue the course without classroom supervision.

3. Emphasis was changed from the specifying of a definite number of individual courses as a requirement for the degree to the plan of awarding the degree for the satisfactory completion of a substantial coördinated program of study.

4. Opportunity for initiative was to be afforded by special work. In the laboratory work of the electrical engineering department, for example, the standard laboratory experiment has been replaced by original projects and students are encouraged to originate experiments for themselves.

Elective Curriculum

Under the elective curriculum plan the student arranges his program of study. The only restrictions are that the program shall be substantial and that it shall have a definite purpose. In order to obtain a degree with designation of field the student is required to complete satisfactorily 2 professional courses in that field. The program must be approved by the administrative board but, so far as I know, the board has required little if any change in the programs that have been submitted by the students. In fact, nearly all the changes are made by the students themselves as they learn from time to time of adjustments which they feel are better adapted to their requirements.

The student, particularly in his freshman year, obviously requires some assistance. This is given primarily by his faculty adviser, although the student is free to and does consult other members of the faculty. Students also obtain considerable information from their fellow students, particularly from the upper classmen. When he enters as a freshman, the student is assigned an adviser in the particular field in which he expresses the most interest, such as electrical engineering, for example. His adviser determines as far as possible the particular phase of the field in which the student seems most interested or to which he is best adapted, although in the freshman year it is not highly important that this be known. If, for example, the student chooses the field of electrical engineering or electric communication engineering in his freshman year, he must plan his sequence of studies so that he will be prepared for the professional courses in that field which usually are taken during the senior year. Assume that one student is interested in electric-power engineering and that he intends to elect power transmission and a-c machinery as the professional courses to be taken during his last year. He would elect substantially the following sequence of studies, which would form the backbone of his program. The subjects bracketed may be taken simultaneously. If it is required that the course be completed in 4 years, they must be taken the same year.

{ Experimental physics
  Mathematics to introduction to the calculus

{ Electrodynamics; or electricity, magnetism, and d-c electrical measurements
  Differential and integral calculus, analytic geometry

{ A-c theory

{ Power transmission
  A-c machinery

If, however, the student is interested in electric communication, a program of studies similar to the following would be arranged:

{ Experimental physics
  Mathematics to introduction to the calculus

{ Electricity, magnetism, and d-c electrical measurements
  Differential and integral calculus, analytic geometry

Differential and integral calculus (advanced course)
Electric oscillations, radiotelephony, radiotelegraphy, electric waves
Electron Tubes

Electric communication
Telephony

Of course some departures from these fundamental sequences are permitted and usually the student supplements these courses with others, usually in advanced mathematics and physics.

The remainder of the program is arranged by the student in accordance with his interests, and usually he will elect courses in related engineering fields. If he feels that he is best adapted to analytic and research work, he will add more courses in advanced physics, mathematics, and engineering. If he is inclined to engineering administration or sales engineering, he will elect courses in the fields of economics and business administration. The electric power engineer may be particularly interested in inductive interference or carrier frequency telephony on transmission lines and will select courses from both the power and communication fields. He will usually complete his program with courses in mechanical and civil engineering, such as thermodynamics, mechanics, statics or kinematics, or hydraulics.

The foregoing elective program appears to solve the problem of the regrouping of curricula along functional lines as proposed by Edward Bennett.[5] However, the program need not be divided rigidly, but each student may select the technical, economic, or administrative subjects which are in accordance with his own abilities and tastes, provided the program which he arranges is substantial and has a definite purpose.

Objections to Elective Program

Certain objections to this elective curriculum may be raised. A number of possible objections were considered before the plan was put into effect. It was feared by some that students would elect a group of easy subjects but this would not fulfill the requirements for a degree. Actually, instead of electing the easier subjects, the tendency has been for students to undertake too many difficult courses. This is sometimes done against the counsel of the adviser. Later, the majority of such students drop or change courses to balance the program. This method of learning by experience is better for the student than to have the faculty decide for him how extensive a program he should carry. However, some students of unusual ability do carry heavy programs successfully. Their advancement, therefore, is not retarded by their being obliged to keep step with students of lesser ability. As a matter of fact, we find the typical engineering student of today serious and hard working. He realizes that only by achievement that is much above the average will he be able later to find a place under present competitive conditions.

The objection may be raised that with the elective curriculum the student will be deficient in cultural and humanistic studies, tending to make him a narrow technician. In his first 2 years it is difficult for the student to complete his program with technical studies only. Practically all the technical courses require physics and mathematics through the calculus as preparation, so that the number of technical courses which the student can take during his first 2 years is limited. Moreover, if he does elect too many technical courses in a single year, he finds that the accompanying laboratory work requires too much time. He also learns by experience that a program entirely of technical subjects has a danger of becoming dull and monotonous, and that the program may be leavened by the election of a few nontechnical subjects.

Also, it should be remembered that in a university the student does not acquire his broader training entirely from classroom work. He makes contacts with students having other interests, and in some universities, including Harvard, it is arranged that students of widely divergent interests shall live together in a single house. Under such conditions students obtain an added breadth of education over that given in the classroom. In consultations with students, I have seen this contact reflected in their election of certain nontechnical studies because their interest had been aroused in such studies by discussions with nonengineering associates.

It may also be objected that the student is too immature to select wisely his own program, and in the beginning he may not know exactly the field of engineering to which he is best adapted. This last criticism also applies to the fixed curriculum. However, with the elective curriculum the student necessarily consults with his adviser when he enters his freshman year, and he immediately obtains a much clearer picture of the engineering profession than he would by the usual formal registration in a number of listed subjects. As is true in most engineering schools, the preparatory subjects of the first year, and to a large extent those of the second year, are common for several fields of engineering and no harm is done if the student does not select his specific field during his first or second year. As a matter of fact, many engineers have attained success in fields of engineering quite different from those in which they were specifically trained.

However, with the elective curriculum the student realizes that the responsibility of arranging the program is his and he starts immediately to make inquiries and to gather facts. He consults his fellow students, particularly the upper classmen, his adviser, his parents, and frequently graduates and practicing engineers. From these various sources of information he usually comes to a tentative decision and then discusses with his adviser the basis on which his decision rests. This development of inquisitiveness and self-analysis on the part of the student is far more important educationally than following blindly a ready-made synthesized program, however carefully it has been prepared. It is natural for the student to take far more interest in subjects which he himself has selected than in those which he is compelled to take.

Incidentally, the entire procedure is stimulating to the faculty. Students are keen to appraise courses at their true value and they are not likely to register in those courses which have little merit.

Reading Period

In 1927 Harvard adopted the reading period whereby, in courses not regularly open to freshmen, formal classroom work at the option of the instructor could be terminated approximately 3 weeks before the end of the term. By reading and other assignments the student completes the course by himself, although he is encouraged to consult with his instructors when he finds it desirable to do so. The primary object of the reading period is to develop the habit of self-education.

At first the reading period was not adopted widely by the engineering faculty. It was felt that at best the entire term was too short a time for imparting the amount of scientific material that the student should know, and that the rate of assimilation is higher under the close supervision of the classroom. However, on reflection, it was realized that the development of self-education and responsibility in the student is far more important than an added number of scientific relationships, and so now the reading period is employed in a majority of the electrical engineering courses above elementary grade.

Reading period assignments are necessarily varied in character. However, most teachers attempt to assign work which requires the students to study current technical publications and reference books, and thus to use the libraries. Students know that in the examination, emphasis will be placed on the reading period assignment and it is found that they actually master their assignments. They assert that they work harder during the reading period than during the other part of the term. A surprisingly rapid development in the student usually occurs during this reading period, due to the fact that instead of regarding the course as consisting of so many designated hours per week in which installments are written in his notebook, he now looks at it in perspective and is able to see it as an integrated whole. Undoubtedly relief from regular attendance in the classroom, which toward the end of the term may become a bit monotonous, has a stimulating influence.

Coördinated Program as Requirement for Degree

Although in a large university it is difficult to teach diverse subjects except as separate units, under the present plan at Harvard the degree is awarded not for completion of a definite number of distinct courses, but rather for satisfactory completion of a coördinate program of studies. The following is quoted from the catalog:

"The degree of bachelor of science in engineering will be conferred on students who complete a program of study, arranged with a definite purpose, ordinarily requiring 4 years of study and consisting largely of mathematics and science."

Electrical Laboratory Work

The object of laboratory work is threefold; to supplement the classroom theory with engineering experience; to familiarize students with the actual manipulation and the practical connections of electrical apparatus; to train students in the methods of planning and conducting an engineering project.

Laboratory work is usually conducted by assigning definite experiments to be performed weekly or at regular short intervals. The plan of issuing direction sheets specifying the laboratory procedure in detail has been discarded at Harvard as not adapted to the development of initiative and resourcefulness in the student; although even with this method the student must necessarily gain some engineering experience and familiarity with the apparatus. An improved method, employed to a considerable extent, is first to require students to study the test apparatus and with a little guidance from an instruction sheet, to submit a preliminary report before the experiments can be performed. This method trains students in the methods of planning and conducting engineering projects. The procedure at Harvard, however, goes farther. As soon as the student has become sufficiently well acquainted with the laboratory equipment and procedure, the laboratory work, instead of consisting of a number of single experiments each performed in one short laboratory session, consists of a few projects which are relatively comprehensive in extent. An instruction sheet designates briefly the particular apparatus, the assignment, and the date on which the final report is due. The student is required to submit a satisfactory preliminary report before he is permitted to perform the experiment. He is free to write the preliminary and final reports when and where he sees fit, except that the final report must be submitted on the date specified. He plans the experimental work and makes the arrangements for the use of the apparatus. Since the experimental work usually involves longer periods of time than the usual laboratory session, it devolves on the student to plan with some care the tests which are to be made and to coördinate the experimental work so that there is no unnecessary duplication, and so that the laboratory time is used in the most efficient manner. There is every incentive for the student to do the work efficiently since he can use the time saved to considerable advantage.

As one example of the method, the separate tests which are usually conducted on a dynamo, such as the saturation curve, the shunt generator characteristic, the compound generator characteristic, the shunt motor characteristic, the compound motor characteristic, the stray power and the determination and separation of losses, are conducted as a single comprehensive project rather than as a number of separate experiments.

Combining Reading and Laboratory Work

An example of combining the reading period assignment with the laboratory work is our requirement that in the reading period occurring at the end of the first semester, the students write the preliminary report for an experiment on a grid-controlled mercury-vapor rectifier and inverter. When they begin their study, the apparatus and its principles of operation are entirely new to them and their only

sources of information are the current technical books and periodicals. Yet, of themselves, they acquire sufficient understanding of the underlying principles of the tube and its methods of operation to write a comprehensive preliminary report and, as part of the midyear examination, to analyze the apparatus and its operation. The experimental work of the project is performed during the first half of the second semester.

At all times students are encouraged to suggest or arrange laboratory experiments on apparatus or subjects which interest them personally, and many students do this.

The advantages of this system of conducting laboratory work are many; it develops initiative and planning in the student; his sense of responsibility is developed; he comes to consider the apparatus which he tests and the laws governing its action as a coordinated whole rather than as a number of separate entities. Moreover, the student can arrange the hours to fit with his other activities. Also, freedom of schedule is quite important in some cases since it gives students opportunity to earn money by outside work and to engage in other activities which regular laboratory hours would prevent.

Conclusions

The foregoing plan of engineering training has been in full operation for nearly 2 years so that its ultimate effects, particularly after graduation, cannot be determined positively yet. Some desirable changes in the attitude of the students have been noticed, however. Frequent consultations make both the students and the faculty better acquainted; the students know themselves much better; they go about their work with a more serious and more mature attitude; there is a distinct improvement in the general scholastic standing. This last, of course, might be attributed to a more intelligent student body. It is not claimed that the methods which are described are the best, although no one will dispute the desirability of the objects. With experience changes will undoubtedly be made, for engineering education can be improved only by continued trial and experiment. It is realized that so single method may be best for all engineering schools. However, this plan is admirably adapted to the educational system of Harvard College and the other departments of the University, also on the elective basis, and they offer many subjects from which the engineering students may choose.

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Split Winding Transformers

A discussion of the application of and advantages derived from the use of split winding transformers for separating bus sections and for avoiding undue concentration of power from high voltage lines. An explanation is given of the characteristics of these units with respect to the reactances and the effect of load unbalance on the windings.

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INCREASE in the size of units and power systems and in the number of interconnections has resulted in operating conditions much more complicated than were encountered in the days of small individual systems. This additional complication in operation can only be justified by improving the over-all efficiency of the system so that power can be sold more cheaply and by the ability of the power company to give more and better service.

Naturally the tying together of larger units or systems results in more concentration of power as well as a greater area being controlled. If tying together these power areas does not result in an improved service, the gain of the interconnection is only partially realized.

One of the principal difficulties of the larger systems has been that of keeping the disturbances resulting from system short circuits within the desired limits. This can be accomplished in several ways:

1. By improving the operating performance of the oil circuit breakers and relays so as to remove the source of trouble as quickly as possible.

2. By increasing system reliability by improvements in design and construction of the component parts, so that the actual number of failures is decreased.

3. By laying out the system so that only a limited area can be affected by the faults which do occur.

There have been several articles published on the first in the last few years showing the improvements made in oil circuit breakers and relays so that there

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is no need to discuss this subject here. Similarly, the manufacturers have been improving the quality of their products, and the power company their installations, so that the failures per hour of service per kva have been decreased.

It is the purpose of this paper to discuss the split winding transformer and to illustrate what a practical device it is for use in the third method by limiting the effects of the faults that do occur.

Split Winding Transformer and Its Application

The split winding transformer is a multiwinding transformer in which 2 or more of the circuits are for the same voltage and intended for connection to independent sources of loads. The split circuits are normally arranged so that they have approximately the same reactance to the other windings. Care also is taken to have a relatively high reactance between them to act as a transfer reactance to limit the transfer of current during disturbances.

There are three major system arrangements in which the split winding transformer may give important advantages in system design. These are:

1. One large split winding transformer may be used in place of smaller banks of straight transformers for feeding 2 or more transmission lines.
2. A split winding transformer may be used to divide large blocks of transmitted power among low voltage buses and thus eliminate the concentration of energy.
3. The split winding transformer may be used to obtain bus sectionalization just as the double winding generators have in stations for lower voltage.

Power system ties have been increasing in size and voltage so that an appreciable amount of power can be exchanged between systems if necessary. These ties can be made using straight 2-winding transformers and 1-circuit transmission with the power taken from one point on each system, or the ties can be made with 2 completely independent lines and transformers or, finally, transformers with split high voltage windings can be used with 2 transmission lines connecting the systems.

The comparison of 2 lines with the split winding transformer, or with 2 independent transformers, brings out the following salient features. Larger transformers may be used with resultant lower costs, losses, and weight per kva for the split winding arrangement. The one circuit reactance can be made higher than the reactance of the smaller individual transformer, with the result that the fault kva will be less for line faults. At the same time, the split winding transformer can be so designed that the power transmitted through one line only, with the other line out of service, can be as large as that which could be transmitted through one of the lines used with independent transformers. However, the 2 lines using independent transformers have the advantage that transformer outage affects only one circuit.

In making a comparison between one power line and transformer with the same capacity as 2 lines with a split winding transformer, it becomes simply a comparison of costs versus reliability with costs favoring the one single transmission line and reliability in favor of the split winding transformer and 2 lines.

The split winding transformer also has been used with one high voltage winding and the low voltage winding split into 2 circuits. The power systems are tied together on the high side with a single transmission line, and the low voltage windings are connected to different bus sections of the station at the distribution load centers. With transmission lines capable of carrying 100,000 kva or more it becomes increasingly advantageous to be able to divide this power among different bus sections for good operating conditions. Also, by this method the size of circuit breakers both as to current rating and interrupting capacity can be decreased. The reduction in the current carrying capacity of these large breakers may be necessary in some cases since the actual current to be handled otherwise is beyond that for which any breaker has yet been designed.

In some power systems where the distribution of energy has been at from 24 to 27 kv the autotransformer has been used to step up the voltage from the generator to that required for the distribution system. With this type of system arrangement the use of the split winding transformer has the same application as the double winding generators have for systems of lower voltage.[1,2,3]

The Brooklyn Edison Company uses autotransformers in its 770,000-kw Hudson Avenue station to step up the generator voltage to 27.6 kv. This station, which was designed initially in 1922–23, has at the present time 3 50,000-kw single-shaft units, an 80,000-kw and 2 110,000-kw cross-compound units, and 2 160,000-kw single-shaft units. The last 2 units use split winding autotransformers in stepping up the generator voltage whereas the earlier units used standard autotransformers. Even with the installation of the last 2 units, which have more than 3 times the rating of the original units, the interrupting requirements of the oil circuit breakers have been kept the same, due to the rearrangement of the station and to the use of the split winding autotransformers.[4]

The application of the split winding transformer can best be shown by the fact that more than 1,250,000 kva of this type have been built in the few years that they have been available. Some 750,000 kva of these units are in autotransformers or straight transformers with the high voltage winding split. The voltage classifications used are 15, 25, and 37 kv.

The high voltage power transformers so far built have had the low voltage windings split, the split winding used varying from 22 to 132 kv. The high voltage windings varied in voltage from 110 to 230 kv. Methods of connecting these transformers are shown in Figs. 1 and 2.

Operating Characteristics

Whether a winding is split to reduce the short circuit kva, to permit maintaining voltage and carrying load on one circuit when the other circuit is short circuited, or for any other purpose described above, these results are obtained by a proper selection of transformer reactances. Both circuits of the split

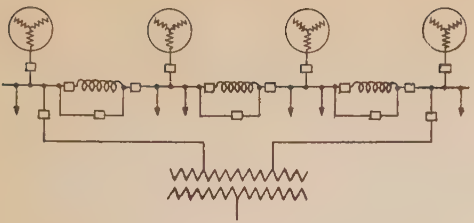
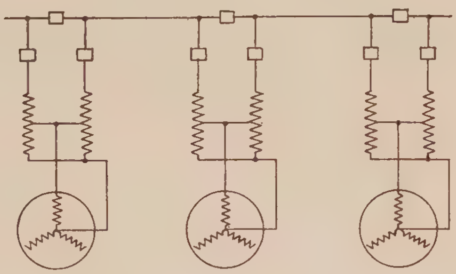


Fig. 1. Split winding transformer for transmitting a large block of power

Fig. 2. Split winding autotransformer used in station bus arrangement

The transformer is applicable to either the star or ring bus



winding of a typical split winding transformer are of equal capacity and have the same reactive characteristics; that is, they have the same regulation drop when equally loaded, carry equal currents when connected to the same bus, draw the same kva when short circuited, etc. As a result of this symmetry, a few simple equations tie together the reactive characteristics of split winding transformers in such a manner that none of them can be changed without changing some other one. These equations are perfectly general in the sense that they apply regardless of the internal connections and construction of transformers. The same equations apply for autotransformers provided all reactances are taken as effective values at terminals.

Throughout this paper the following terminology will be used as indicated in Fig. 4. For a transformer with a single circuit winding *A* and with winding *B* split into 2 circuits, *B1* and *B2*, the total power transmitted from *A* to *B* will be called the "through" power or load. The power flowing from *B1* to *B2* will be called the "transfer" power or load. Operation from *A* to *B1*, with *B2* idle, will be called "1-circuit" operation, and the corresponding load "1-circuit" load. The expressions "balanced load" or "balanced operation" will be used to describe operation with *B1* and *B2* equally loaded at the same power factor. "Unbalanced load" and "unbalanced operation" will mean operation with *B1* and *B2* unequally loaded. "Unbalanced" operation may be viewed, of course, as the result of superposition of a "through" load and a "transfer" load, and the degree of unbalance can be specified clearly by specifying these simultaneous loads. Since, however, the *B1* and *B2* loads are usually of the same power factor so that the load on *A* is equal to their arithmetical sum, this load may be taken as 100 per cent and the degree of unbalance then may be specified conveniently by stating the percentage of total power flowing through each circuit. As an example 45//55 per cent load division will mean that 45 per cent of the total load, and consequently of load on *A*, is carried by *B1* and 55 per cent by *B2*.

The reactance from *A* to *B1* and *B2* in multiple will be called the "through" reactance and will be denoted by $X_{A-B1//B2}$. The reactance from *B1* to *B2* will be called the "transfer" reactance X_{B1-B2}. The reactance from *A* to *B1* will be called the "1-circuit" reactance X_{A-B1}. All reactances will be expressed in per cent based on some reference kva. In using the curves and formulas of this paper care must be exercised to have all reactances reduced to some common kva basis.

Reactances

Split winding transformers have been built with ratios of transfer to through reactance ranging from a little less than 4 up to approximately 18. Theoretically this ratio can have any value from zero to infinity. This flexibility is a striking advantage over older methods of splitting a circuit. Thus if 2 separate lines were connected through reactors to the same terminals of an ordinary transformer the total theoretically possible range of values of the ratio of transfer to through reactance would be contained between the limits of zero and 4, with the upper limit unobtainable in practice as it could be reached only if transformer reactance were zero. If 2 similar transformers of ordinary type were used, permanently connected in multiple on the single circuit side and connected to 2 separate circuits on the split side of the system, the ratio of transfer to through reactance would be equal to 4 and could have no other value.

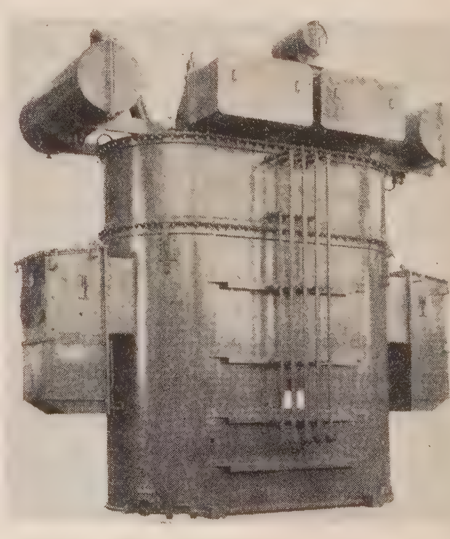
The through, the transfer, and the 1-circuit reactances of a split winding transformer must satisfy the relations shown in Fig. 5 and given by the following equation:

$$X_{A-B1//B2} = X_{A-B1} - {}^1/_4 X_{B1-B2} \qquad (1)$$

Several important conclusions can be drawn from eq 1. If any 2 of the 3 reactances involved are specified, the third reactance becomes fixed, so that one cannot assign arbitrary values to all 3 reactances. Thus, for instance, if the through reactance $X_{A-B1//B2}$ is specified as 8 per cent and the transfer reactance X_{B1-B2} as 40 per cent, the 1-circuit reactances X_{A-B1} and X_{A-B2} must be 18 per cent, and cannot have any other values.

Even assigning arbitrary values to 2 out of 3

Fig. 3. Split winding transformer rated "WC - 60 - 20,000 kva, 110,000–13,700 / 23,750 V // 13,700/ 23,750 V" with independent load ratio control on the 2 low voltage circuits



reactances involved in eq 1 may lead to a physically impossible or to an economically impracticable design, depending on the resultant value of the reactance left unspecified. Assume for instance that the 1-circuit reactance and the transfer reactance have been specified as 15 per cent and 64 per cent, respectively. These values, substituted in eq 1, give −1 per cent for the through reactance. Therefore, it is physically impossible to obtain the specified reactance values. If the 1-circuit and the transfer reactances are specified as 15 per cent and 52 per cent, respectively, eq 1 gives + 2 per cent for the through reactance. This value, although theoretically speaking a possible one, is unreasonably low and in most cases would necessitate an extremely expensive design, so that the specified reactance values would be, practically speaking, unobtainable.

Referring once more to eq 1, 1-circuit reactance cannot be lower, and in most cases will be considerably higher, than the through reactance. On the basis of constant through reactance, the higher the specified value of transfer reactance is the higher will be the 1-circuit reactance. This is important when 1-circuit operation is expected, because excessive values of 1-circuit reactance may result in unsatisfactory 1-circuit operation due to excessive voltage regulation and load losses.

Short-Circuit Conditions

Two conditions of symmetrical 3-phase short circuit on *B1* will be considered: first, when voltage is maintained only on the single circuit winding *A*; second, when voltage is maintained not only on *A*, but also on *B2*. For all ratios of transfer to through reactance, except 4, short circuits will be heavier with voltage maintained on both *A* and *B2* than with voltage maintained only on *A*.

The reactance limiting the short-circuit kva, when *B1* is short circuited and full voltage maintained on *A* only, is found by rewriting eq 1 as:

$$X_{A-B1} = X_{A-B1//B2} + {}^1/_4 X_{B1-B2} \qquad (2)$$

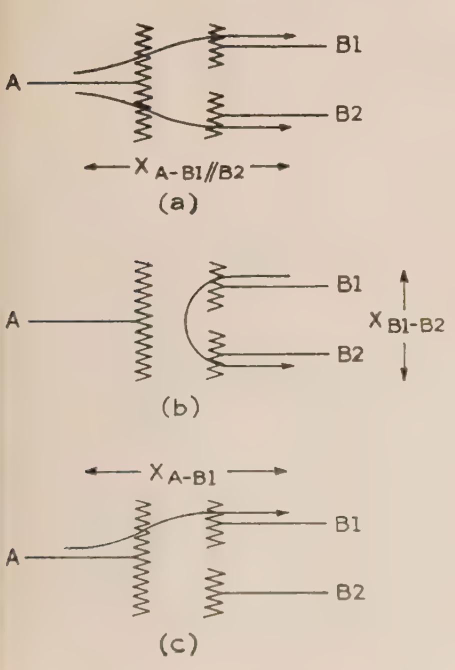


Fig. 4. Loads and reactances

(a) Through load and through reactance
(b) Transfer load and transfer reactance
(c) One-circuit load and one-circuit reactance

This equation shows that with a given through reactance, short circuit kva always is reduced by splitting winding *B*. With transfer reactance equal to 4 times the through reactance the short circuit

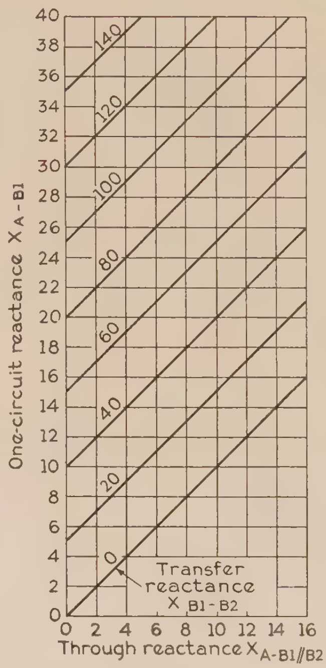


Fig. 5. Relation of reactances

All reactances in per cent on common reference kva

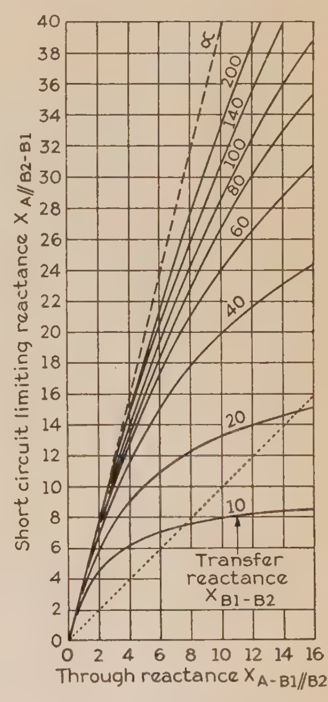


Fig. 6. Short-circuit limiting reactance. Short circuit on B1, voltage maintained on A and on B2

kva is just half what it would be if the *B* winding were not split, and further reduction in short-circuit kva down to any desired value can be obtained by increasing the transfer reactance.

The reactance limiting the short-circuit kva when *B1* is short circuited and voltage maintained on both *A* and *B2* is given by the following equation, represented graphically in Fig. 6:

$$X_{A//B2-B1} = \frac{4X_{A-B1//B2}\, X_{B1-B2}}{4X_{A-B1//B2} + X_{B1-B2}} \qquad (3)$$

As shown by the straight dotted line on Fig. 6, for a given through reactance short circuit kva is reduced by splitting winding *B*, provided the transfer reactance is greater than $^4/_3$ of the through reactance. With the transfer reactance 4 times the through reactance the short-circuit kva is half what it would be if the *B* winding were not split. A rapid increase in the transfer reactance will be required to obtain a further reduction in short-circuit kva. Transfer reactance equal to 12 times the through reactance will give short-circuit kva equal to $^1/_3$, and, as an absolute limit, transfer reactance equal to infinity will give short-circuit kva equal to $^1/_4$ of what it would be if the *B* winding were not split. If still lower values of short-circuit kva are required the *B* winding will have to be split into more than 2 circuits.

Under balanced load the regulation from the terminals of the single circuit winding A to the terminals of each circuit of the split winding B is the same, and may be calculated as for any 2-winding transformer using the through impedance $Z_{A-B1//B2}$ and the through load.

For unbalanced loads the regulation may be calculated by well known methods, treating the transformer with windings A and B, the latter split into circuits $B1$ and $B2$, as a 3-winding transformer with windings A, $B1$, and $B2$.[5]

An alternative method consists of resolving the unbalanced load on winding B into the 2 components of the through and the transfer loads, and calculating separately the voltage drops due to these components. For the through load the impedance is $Z_{A-B1//B2}$ and for the transfer load Z_{B1-B2}. It is obvious that half the voltage given by the product of transfer load times transfer impedance will appear at the terminal $B1$ and the other half, with reversed sign, at the terminal $B2$. It follows that under unbalanced loads the terminal voltages $B1$ and $B2$ are unequal, and that the transfer component of the load raises one of them and lowers the other.

This shows that voltage regulation under badly unbalanced loads will be poor in transformers with high transfer reactance, unless operating at power factors close to unity. However, this same characteristic may be taken advantage of to design split winding transformers such that with one circuit of the split winding short circuited the terminal voltage of the other circuit is kept up, thus retaining the load on that circuit.

Neglecting resistances, with 100 per cent voltage maintained on terminals A, and with $B1$ open circuited and $B2$ short circuited, the voltage rise at the terminals $B1$, expressed in per cent of rated voltage, is:

$$\Delta E = \frac{X_{B1-B2} - 4X_{A-B1//B2}}{X_{B1-B2} + 4X_{A-B1//B2}} \times 100 \qquad (4)$$

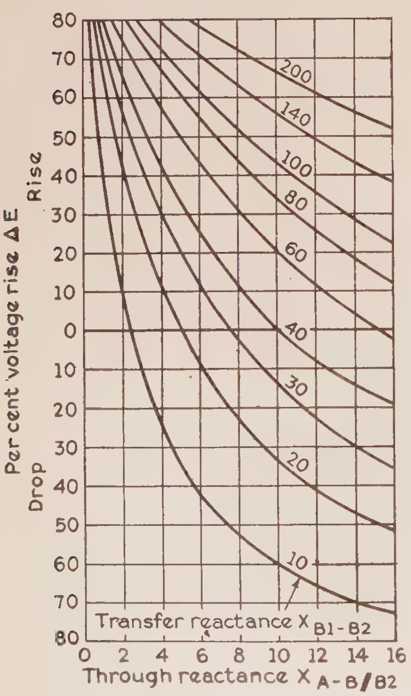


Fig. 7. Voltage rise or drop under short circuit. Voltage rise or drop at B1 with B2 short-circuited and voltage maintained on A. All reactances in per cent on common reference kva

This rise may be found to be negative, indicating a drop in voltage.

Figure 7 is a graphical representation of eq 4 which shows that if the transfer reactance is more than 4 times the through reactance a short circuit on $B2$ will be accompanied by a voltage rise at terminals of $B1$. A moderate rise is usually desirable as it helps to retain the load on $B1$. Extra high values of transfer reactance may give excessive values of voltage rise. As an example, a design with 10 per cent through reactance and 100 per cent transfer reactance will give a rise of 43 per cent, which may be altogether too high for the connected apparatus. The full value of this rise will appear at $B1$ terminals only if negligible load is connected to $B1$ and if the voltage on A is maintained during a dead short circuit on $B2$. Usually this is not the case.

When the ratio of transfer to through reactance equals 4, a short circuit on $B2$ will leave the terminal voltage of $B1$ unaffected. As an example, a design with 10 per cent through reactance and 40 per cent transfer reactance will have zero voltage rise at terminals of idle circuit $B1$ when circuit $B2$ is short circuited and 100 per cent voltage is maintained at terminals of winding A.

If the transfer reactance is less than 4 times the through reactance a short circuit on $B2$ will be accompanied by a voltage drop at the terminals of $B1$. This may be objectionable if the voltage drop is excessive. For example, a design with 10 per cent through reactance and 20 per cent transfer reactance will give a voltage drop of 33 per cent.

LOSSES

The no load loss and the load losses for balanced loads present no peculiarities and are usually only slightly higher than the normal losses of transformers of the same rating but without split windings.

Under unbalanced loads the load losses always are higher than under balanced loads of the same total kva. In fact, under unbalanced loads the load losses are given by the sum of load losses due to through load plus load losses due to transfer load so that the effective resistance of a split winding transformer may be expressed as:

$$R_{eff} = R_{A-B1//B2} + t^2 R_{B1-B2} \qquad (5)$$

where all resistances are effective values at terminals expressed in per cent based on some common reference kva; t is the transfer load per unit of through load. In Fig. 8 is shown a graphical representation of eq 5.

In eq 5 the term $t^2 R_{B1-B2}$ represents the extra loss due to load unbalance. This loss varies as the square of transfer load and is proportional to the transfer resistance R_{B1-B2}. All the resistances of eq 5 are a-c resistances; that is, they include eddy and stray losses in addition to straight d-c resistance. The transfer resistance usually would be higher than the through resistance even if no eddy and stray losses were present because circuits $B1$ and $B2$ would normally be designed for a smaller kva capacity than winding A. Eddy and stray losses are caused

by leakage flux; since transfer reactance is usually higher than through reactance there usually will be more leakage flux per kva of load for transfer loads than for through loads. If, therefore, eddy and stray losses are taken into account as they must be in any practical design, it will be found that in most cases transfer resistance is much higher than through resistance, and that increasing the ratio of transfer to through reactance will increase the ratio of transfer to through resistance.

It follows, therefore, that in transformers with a high ratio of transfer to through reactance the load losses will increase faster with load unbalance than in designs with a moderate ratio.

Design Features

Split winding transformers may be built as 3-phase or as single phase units, with windings connected Y or delta, as straight transformers or as autotransformers. The split winding may consist internally of 2 entirely independent circuits, or it may be only partially split. Fig. 9 shows, on a single phase basis, 5 fundamental internal connection diagrams. In practice, in addition to these schemes, their various modifications and combinations may be used.

The arrangement of Fig. 9a is the simplest possible arrangement and may be used for all values of the ratio of transfer to through reactance by properly interlacing circuits *B1* and *B2*. If the required degree of interlacing is difficult to obtain, the scheme of Fig. 9b may be used to advantage. The transfer reactance may be reduced to any desired value by reducing the percentage of turns in the split portion of the winding, so that no interlacing whatever is required. Another scheme of avoiding the necessity of interlacing the 2 circuits of the split winding is shown in Fig. 9c. If coils Nos. 1 and 4 are electromagnetically remote from coils Nos. 2 and 3, the ratio of transfer to through reactance is 4. Both higher and lower ratios can be obtained by other groupings of the 4 coils.

The simplest internal connection diagrams for autotransformers, split on the high voltage and on the low voltage side respectively, are shown in Figs. 9d and 9e. Figure 9d is an adaptation of the scheme of Fig. 9a to an autotransformer split on the high voltage side. In fact, Figs. 9a, 9b, and 9c can be applied for autotransformers split on the high voltage side, by simply connecting the single winding *A* in series with the split winding *B*. Winding *A* will become then the common winding and winding *B* the split series winding of the autotransformer. Figure 9e is an adaptation of the scheme of Fig. 9c to an autotransformer split on the low voltage side.

Split winding transformers may be provided with taps, with or without load ratio control, for independent voltage control in both circuits of the split winding. If independent control is not desired, internal connections such as that shown in Fig. 9b permit varying the terminal voltages of both circuits by means of only one set of taps located in the unsplit portion of the split winding.

From the viewpoint of voltage stresses, both of operating frequency and of high frequency, each circuit of a split winding must be considered as an independent winding and must be insulated accordingly.

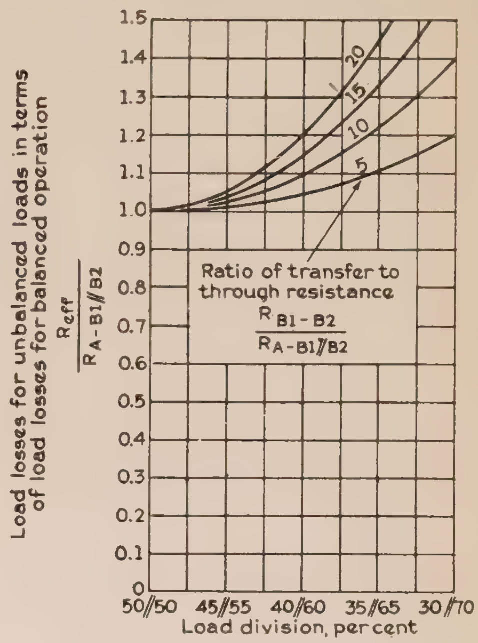


Fig. 8. Effect of load unbalance on load losses. All resistances in per cent on common reference kva

Transformers With 2 Split Windings

Transformers have been built with a single circuit primary, a double circuit secondary, and a double circuit tertiary; with symmetrical reactances from the primary to the secondary circuits and also from the primary to the tertiary circuits.

Depending on the degree of symmetry and on the values of reactances between various circuits, transformers with 2 split windings may have strikingly different operating characteristics. Thus a 2-winding transformer with 2 circuits *A1* and *A2* in the primary *A* and 2 circuits *B1* and *B2* in the secondary *B* may be designed with symmetrical reactances

$$X_{A1-B1} = X_{A1-B2} = X_{A2-B1} = X_{A2-B2}$$

In this transformer, current unbalance on the *A* side does not produce any current unbalance on the *B* side and *vice versa*. Hence, for any unbalanced loads, including short circuits, the transformer behaves as though it were split only on the side carrying the unbalanced load.

Entirely different characteristics are obtained by locating windings *A1* and *B1* electromagnetically remote from windings *A2* and *B2*. In this case, so far as reactances are concerned, there are in effect 2 transformers, one with windings *A1* and *B1* and the other with windings *A2* and *B2;* and this result is achieved without an appreciable sacrifice of the advantages of large unit size. Any load unbalance on the *A* side tends to be reflected on the *B* side and affects all the apparatus connected to the *B* side, depending on its characteristics, as a current or a voltage unbalance.

A variety of intermediate designs can be worked out between these extremes.

Windings Split Into 3 or More Circuits

In some rather special cases it may be advantageous to split a winding into more than 2 independent circuits. Let us define a symmetrical design as a design in which all the circuits of the split winding possess the same reactive characteristics, so that they have the same regulation drop when equally loaded, carry equal currents when connected to the same bus, draw the same kva when short circuited, etc.

Evidently, in a symmetrical design, all the reactances from the single circuit winding A to any circuit of the split winding B must be equal, and also all the reactances between any 2 circuits of the split winding B must be equal, that is:

$X_{A-B1} = X_{A-B2} = X_{A-B3} = X_{A-B4}$, etc.

$X_{B1-B2} = X_{B1-B3} = X_{B1-B4} = X_{B2-B4} = X_{B3-B4}$, etc.

The effect of the number of circuits in the split winding on transformer characteristics is shown in Fig. 10 where the curves are plotted against the ratio of transfer to through reactance, with the number of circuits as a parameter.

Fig. 10a gives the ratio of 1-circuit reactance to through reactance. Transformers with the same through and transfer reactances but with a different number of circuits in the split winding will have different values of 1-circuit reactance. For example, a transformer with 10 per cent through and 40 per cent transfer reactances will have 20 per cent 1-circuit reactance if it has 2 circuits in the split winding, 25 per cent with 4 circuits, and 27.5 per cent with 8 circuits.

A symmetrical design with several circuits in the split winding retains its symmetry when operating with some of the circuits idle. The reactance for such operation also can be obtained, therefore, from Fig. 10a. As an example, a transformer with 3 circuits in the split winding, with 10 per cent through reactance and 48 per cent transfer reactance, will have the following reactances:

Operating on all 3 circuits.......................... 10 per cent
Operating on any 2 circuits.......................... 14 per cent
Operating on any one circuit.......................... 26 per cent

Having found the reactances as in the examples above, regulation and short-circuit kva, are readily determined on the assumption that voltage is maintained only on the single circuit winding.

Fig. 10b shows that with one circuit of the split winding short circuited and voltage maintained on the remaining circuits of the split winding and on the single circuit winding, for designs with any number of circuits the short-circuit limiting reactance increases with increasing transfer reactance, following a curve that gradually flattens out and approaches a horizontal line. So far as short-circuit protection is concerned, there is little to be gained from any further increase in the ratio of transfer to through reactance. If a higher ratio of short-circuit limiting reactance to through reactance is desired, it will have to be obtained by increasing the number of circuits in the split winding.

Fig. 10c shows that the ratio of transfer to through

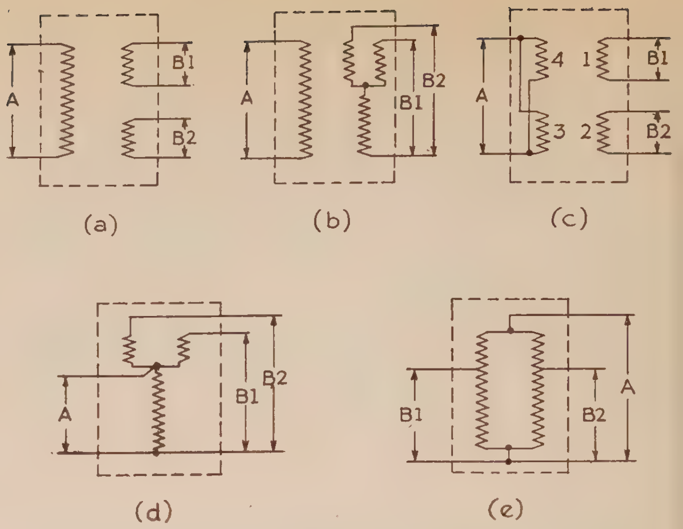


Fig. 9. Internal connections for split winding transformers (above) and autotransformers (below)

reactance must be equal to at least twice the number of circuits in the split winding if a drop in terminal voltage of all circuits, when one of them is short circuited, is to be avoided. It is obvious from design considerations that any increase in the number of circuits would naturally be accompanied by an increase in transfer reactance so that, as a rule, the above requirement is easily met.

If a certain rise in voltage is specified the corresponding ratio of transfer to through reactance is readily determined for any number of circuits. It will be observed that for a given voltage rise the required ratio of transfer to through reactance increases very fast as the number of circuits is increased. In fact, there is a definite limit to maximum voltage rise obtainable with a given number of circuits, and the greater the number of circuits the lower the limit is. It is very fortunate, therefore, that operating requirements usually do not call for a large voltage rise when there are more than 2 or 3 circuits in the split winding.

Curves of Fig. 10 will be exact only for exactly symmetrical designs. Exact symmetry may be difficult to obtain in a practical design, and even approximate symmetry may be difficult to obtain when the number of circuits is large, especially if windings are provided with taps. When applied to approximately symmetrical designs the curves of Fig. 10 will be only approximations.

In many cases there is little justification for specifying a symmetrical or even an approximately symmetrical design. Thus, for instance, when the circuits of the split winding are connected to entirely independent lines, to separate buses, or to separate generators the current division and the regulation drop are obviously controlled by the connected load or by the governor setting and the excitation of the generators. In such cases symmetrical reactances are no more necessary than in any multiwinding transformer. When the circuits are connected to separate lines and these lines are tied together at some distance from the transformer, or when the circuits are connected to a split winding

generator, the reactances of the lines or the reactances of the generator windings will be sufficiently high, as a rule, to make any reasonable departure from exact symmetry in transformer reactances a matter of no practical significance. Even in the rather unusual case when the circuits of the split winding are connected to a common bus equal current division can be obtained without symmetrical reactances provided there are more than 2 circuits in the split winding. Although such a design will not divide currents equally when operating with some of the circuits idle, will not draw the same short-circuit kva regardless of which circuit of the split winding is shorted, and will not give the same voltage rise at terminals of all non-short-circuited circuits, the variations in these characteristics can be usually held within permissible limits.

Summarization

Although the split winding transformer is a relatively new tool for power system design, more than 1,250,000 kva of these units have been built.

By using transformers of this type large blocks of transmitted high voltage power have been divided among bus sections on the low voltage side to eliminate power concentration and improve the normal system operating conditions.

These transformers have been used in station bus arrangements to obtain bus sectionalization with a resultant reduction in the size of circuit breakers required and the elimination of the bus sectionalizing reactors.

Since existing systems in increasing their capacity have used split winding transformers where transformers were required to obtain the proper voltage without increasing the interrupting duty on the existing breakers, there is every reason to believe that these transformers will be advantageous in other existing stations when increased capacity is required, as well as be useful in the building of new stations.

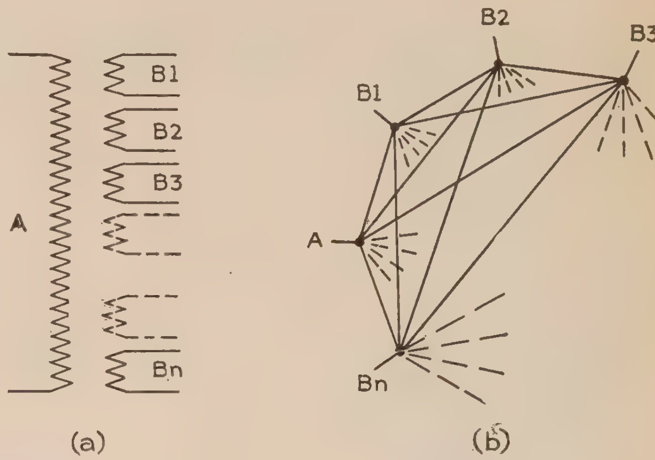


Fig. 11. Equivalent circuit for symmetrical design with "n" circuits in the split winding

(a) Transformer (b) Equivalent circuit

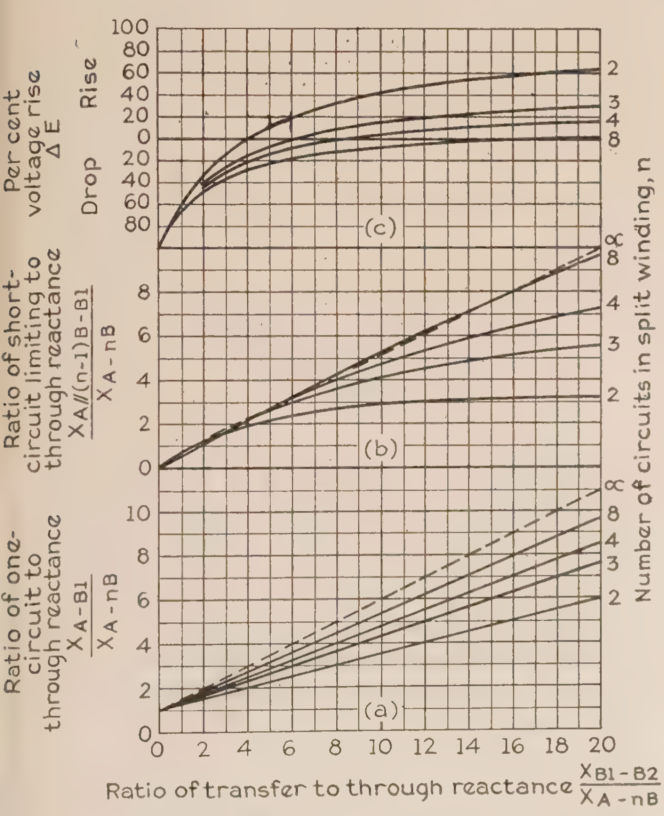


Fig. 10. Characteristics of transformers with one winding split into several circuits

(a) Relation of reactances
(b) Short circuit limiting reactances
(c) Voltage rise or drop under short circuit
All reactances in per cent on common reference kva

The power companies in deciding on the desirable characteristics of a split winding transformer should obviously study the adjacent parts of the system so as to obtain the best coördination possible between the system and the new installation. This is especially true in determining the number of circuits in the split winding.

As far as the transformer itself is concerned, the desirable characteristics may be briefly outlined as follows:

1. Although transformers can be built with windings split into any reasonable number of circuits, designs with more than 2 circuits in the split winding necessarily are more complicated and expensive and should not be specified unless the system itself is split into more than 2 circuits, or an extraordinary reduction in short-circuit kva is required.

2. The best ratio of transfer to through reactance for transformers with 2 circuits in the split winding is approximately 4. If this ratio is less than 3, the effectiveness of split circuit construction in preventing the spread of trouble from one circuit to another is seriously reduced; on the other hand, ratios much higher than 10 are suitable only when no appreciable load unbalance is expected, and when system characteristics are such that over-voltages caused by short circuits present no danger.

3. Transformers with 2 circuits in the split winding have been built with load division ranging in limits from 50//50 per cent to 33//67 per cent. If necessary, transformers can be built for a greater load unbalance. Naturally such designs will be more expensive.

4. Transformers with 2 circuits in the split winding are inherently symmetrical. In transformers with more than 2 circuits, symmetry can be obtained but may require a special design. In many cases, approximate symmetry will meet operating requirements. There-

fore, for transformers with several circuits in the split winding, a permissible range of reactance values, rather than definite values, should be specified.

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Appendix

Denoting the number of circuits in the split winding by n and expressing all reactances in per cent based on some common reference kva, the reactive characteristics of a symmetrical transformer are given by the following equations.

Relation connecting the 3 reactances:

$$X_{A-nB} = X_{A-B1} - \frac{n-1}{2n} X_{B1-B2} \quad (6)$$

wherefrom:

$$\lim (X_{A-B1}) = X_{A-nB} + {}^1/_2\, X_{B1-B2} \quad (7)$$

when $n \longrightarrow \infty$

Relation between reactances and short circuit kva, or short circuit on $B1$ and maintained voltage on $B2$, $B3$, $B5$, etc., and on A

$$X_{A//(n-1)B-B1} = \frac{n^2 X_{A-nB}\, X_{B1-B2}}{2n(n-1)\, X_{A-nB} + X_{B1-B2}} \quad (8)$$

wherefrom:

$$\lim \left[X_{A//(n-1)\,B-B1} \right] = n^2 X_{A-nB} \quad (9)$$

when $\frac{X_{B1-B2}}{X_{A-nB}} \longrightarrow \infty$

Relation between reactances and terminal voltage rise of non short-circuited circuits of a split winding when 1 circuit is short circuited

$$\Delta E = \frac{X_{B1-B2} - 2nX_{A-nB}}{(n-1)\, X_{B1-B2} + 2nX_{A-nB}} \times 100 \quad (10)$$

Wherefrom:

$$\lim (\Delta E) = \frac{1}{n-1} \times 100 \quad (11)$$

when $\frac{X_{B1-B2}}{X_{A-nB}} \longrightarrow \infty$

Referring to Fig. 10, in the equivalent mesh network of a symmetrical split winding transformer all branch reactances from the terminal A to any B terminal are equal to

$$nX_{A-nB} \quad (12)$$

and all branch reactances between B terminals are equal to

$$\frac{n^2 X_{A-nB}\, X_{B1-B2}}{2n\, X_{A-nB} - X_{B1-B2}} \quad (13)$$

A New Porcelain Post Insulator

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A new porcelain post insulator for transmission lines, which is free from radio effect at its operating voltage, is described in this paper. Capacitance measurements are utilized to determine and rate the radio characteristics. Other points of design are described, such as improved leakage path to resist arcing in contaminated atmosphere, greater height to avoid grounding by birds, and increased resistance to destruction by internal cracking, puncture, and breakage.

NEW requirements necessitate the reconsideration of the specifications for pin type transmission line insulation. The following points are submitted as an adequate basis for judging the merits of such insulators.

1. Long life should be insured by a design inherently free from puncture or cracking, with few special details to be watched during manufacture, assembly, and testing. Lack of internal soundness has produced most failures.

2. Resistance to shattering by power arcs, stones, and bullets should be assured. Material should be distributed to avoid extended fragile parts especially if they permit propagation of cracks into the body of the insulator. At all hazards it should be possible to maintain or restore service on the damaged insulator.

3. Accepted ratings and flashover standards should be met.

4. Operation in dirty atmospheric conditions without cleaning is frequently of critical importance.

5. Permanent freedom from radio effects at voltages safely above neutral operating voltage presents the latest problem. This result

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should preferably be accomplished by a design that reduces the cause instead of by the use of superficial coatings or attachments that may deteriorate and aggravate the trouble.

6. Cost must be reasonable for general use.

The degree to which these qualifications have been met by a new porcelain line post is the subject of this paper.

The Line Post Development

In Figs. 1 and 2 are shown the developed form of a porcelain post with recessed tie head. A similar line post with conventional tie head is shown in Fig. 3. A standard pin type line insulator is shown in Fig. 4 for comparison.

The line post insulator consists of a hollow porcelain column having an integral closed end at the top or live end and a hermetically sealed plug in the bottom or open end which is solidly cemented into a rigid metal base. (See Fig. 1.) The porcelain is covered on the outside with numerous small leakage flanges producing what is known as "fog type." In its developed form shown in Figs. 1 and 2, the tying head is formed with an undercut or recessed groove below the tie wire groove, which latter is located in the outer rim of the head. This head permits the conventional method of tying. This modified form is employed to reduce the capacitance of the insulator, by interposing air between the tie wire and the main body of the insulator, a region in which the flux density is relatively high. Large diameter of the tie loop permits low concentration of flux leaving the tie wire.

The degree to which corona and radio effects can be reduced in this low capacitance type of porcelain post insulator makes it unnecessary to resort to special conductive or dielectric coatings around the tie wire. It is also possible to use the conventional form of tire wire without special attention to tightness and kind of material or to surface condition of the wire. In the usual high capacitance insulators, unless specially treated, these factors may cause sparking and reduction of the critical voltage.

Radio Characteristics

Radio effects may be encountered where radio frequency voltages appear as a result of concentrated corona or sparking present through the air, usually between a metal part and the porcelain, and particularly between the tie wire and the porcelain. The problem of eliminating this degree of concentration may be attacked in 2 ways. First, by reducing the flux from tie wire to porcelain, and second, by inreasing the equivalent area of contact or replacing the overstressed air by a non-gaseous filler. Along this second line of attack various coatings and fillers, both conductive and insulating, have been tried, but they are usually subject to deterioration or change, and by increasing the capacitance of the insulator they may cause critical concentration at the pin or between shells.

Reducing the amount of electrostatic flux or charging current passing from the tie wire to the insulator is a more fundamental method of removing the trouble. This can be limited by reducing the capacitance of the insulator. The capacitance of the insulator can be reduced most by removing the conventional pin and supporting the conductor and tie wire on a porcelain post of maximum length above the grounded base and of minimum cross section, since porcelain has a high dielectric constant. It is advantageous to make the porcelain body, especially at the top, as small as practicable.

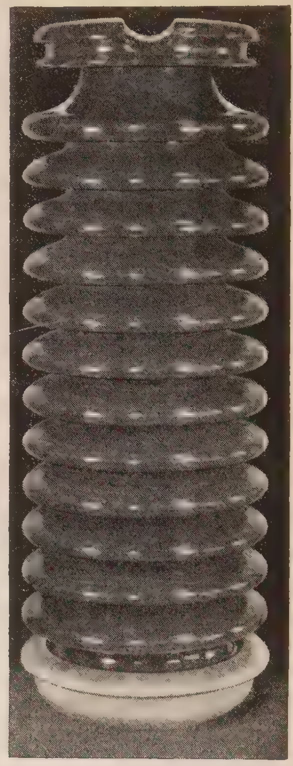

Fig. 1. The new line post insulator for transmission lines

Determination of Radio Effects by Capacitance Measurements

Measurement of electrical capacitance of the insulator affords a possibility of quantitative statement of the effectiveness of different types of insulators in respect to their freedom from radio characteristics. Intensity of electrostatic flux passing from the tie wire into the porcelain is the critically important factor. A significant indicator of the flux entering the porcelain is the capacitance added when the porcelain is placed in position between the tie wire and the ground terminal. Capacitance of line conductor and tie wire are measured while these metal parts are supported in normal relation. Then, the porcelain is put in place between the hardware, and capacitance readings are taken showing a small increase for the porcelain post and a large increase for the pin type. The total capacitance through the porcelain, C_P, can be found by multiplying this added capacitance by the factor $K/(K-1)$ in which K is the dielectric constant. This factor for porcelain is approximately 1.19.

The total flux entering the porcelain from the tie

Table I—Determination of Criterions for Radio Effect

Insulator Type	Point on Curve	Rated Voltage, Kv	Line Voltage to Ground, Kv	Lowest Radio Voltage, Kv	Capacitance, Micromicro farads: Total C_T	Porcelain Removed C_A	Through the Porcelain $C_P = \frac{C_T - C_A}{(K-1)K}$	Length of Tie-wire Contact Inches L, $L = \pi d$	L/C_P
Standard head pin	1	35	20	7	16.6	8.55	9.56	11.1	1.16
Standard head pin	1	45	26	9	18.2	8.08	12.00	11.1	.915
Standard head pin	3	66	38	10.5	16.6	5.25	13.50	15.7	1.16
Standard head line post	4	20	11.5	22	9.32	8.14	1.41	6.28	4.45
Standard head line post	5	66	38	29	5.66	3.90	2.09	14.2	6.8
Recessed head line post	6	66	38	41	5.96	4.54	1.688	18.9	11.2

wire divides into 2 paths. One portion traverses the porcelain directly to the lower metallic grounded terminal, pin, or base. The second part of this flux passes through the porcelain and is diffused to space. This latter fraction is a major portion of the very small amount of flux entering the porcelain in the case of the porcelain post and is a minor portion of the large amount of flux in the case of a standard pin type insulator.

Returning to the total flux entering the porcelain, it is found that if the measured value of this capacitance is low per unit length of tie wire, or circumference of tie-wire groove, the intensity at the contact is low and the voltage for initial radio effect is high. Reciprocals of this ratio are listed in Table I under L/C_P and plotted in Fig. 5, using lowest radio voltages as ordinates. This places the relation on a quantitative basis and shows in a specific way the improvement accomplished by the porcelain line post.

The quantity L/C_P may be taken as a merit figure for the insulator, as shown by the fact that it produces a smooth graph with lowest radio voltages as ordinates. The higher this merit figure, the lower is the flux intensity and therefore the higher the voltage on which the insulator can be used without radio effects.

It will be noted that this graph, when extended, does not pass through the origin, but indicates a positive intercept on the ordinate axis and some value of negative intercept on the L/C_P axis. It is probable that this is due to a small amount of flux leaving the line conductor that does not flow through the critical contact between the tie wire and porcelain. Capacitance measurements made with the line conductor removed tend to confirm this explanation of the intercepts.

Minimum radio voltages and capacitances were measured using 2 turns of No. 8 tie wire and a piece of one-inch conductor about 22 in. long. With 3 turns of tie wire on the recessed line post, the lowest detectable voltage is raised to about 50 kv, which is the greatest increase shown by the additional turn for any type. In general, a greater number of tie-wire turns or larger diameter of wire give higher values of minimum radio voltage.

Table II presents a comparison between conventional and line post insulators on the basis of lowest or starting voltage for radio effects. In Table II, values correspond to 2 turns of No. 6 tie wire. It is found that a practical margin of voltage for minimum radio effect voltage above neutral or operating voltage is available in these post types to offset well-known effects of different kinds of tie wire and different conditions of looseness or roughness of surface or oxidation of the surface of the wire. These factors are of less importance in this type since the flux is reduced to such a very low value.

Values of minimum radio voltage given are conservative as they represent the point at which the initial detectable effect occurs. This is at the start of audibility with maximum volume adjustment on the receiver and with 12 ft of pick-up antenna parallel to the line conductor at 4 ft distance. The start is easily detected audibly or simultaneously on an output meter between the receiver and the speaker. In this way there is no need to be concerned with a calibrated degree of audibility which has been the basis of most of our thinking about radio effects. The practical point at which actual effects would be noticed on a line would occur at some higher voltage and afford another margin of safety. In making these tests for radio effect, the outside disturbances and transformer noise were absent.

Auxiliary devices were not used and are not reported in these tests although any kind of auxiliary treatment that would provide an improvement in usual types should produce some still higher values when applied to this type of recessed tie head line post. This statement is made to emphasize the fact that the method of eliminating concentration by reduction of capacitance is distinct from the remedies which spread the flux or fill in the air

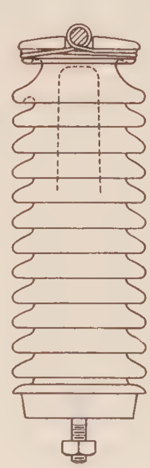

Fig. 2 (left). Line post insulator with recessed head; 66-kv rating

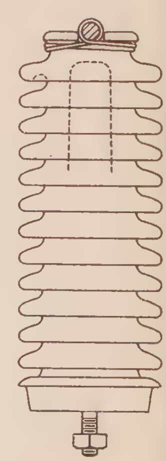

Fig. 3 (right). Line post insulator with standard tie head; 66-kv rating

Table II—Comparison of Radio Characteristics

Kv Rating	Neutral Rated Voltage	Minimum Radio Voltage: Conventional Pin Type	Minimum Radio Voltage: Line Post, Recessed Head
20	11.5	5.5	22
25	14.5	6	32
35	20	7	36
45	26	9	40
55	32	10	43
66	38	10.5	47

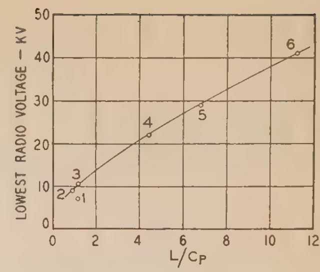

Fig. 5. Curve relating flux concentration to lowest radio voltage

space where the flux tends to produce corona breakdown, whether by the use of conductive coatings and fillers or by dielectric or porcelain filling.

Electrical Characteristics

Electrical considerations also involve dry and wet flashover voltages, freedom from short circuit by birds, freedom from puncture, resistance to flashover under contaminated atmosphere, and maintenance of electrical values after damage by power arc or mechanical breakage. On account of decreased diameter, normal ratings of flashover distance and voltage are attained by slightly greater height than in standard pin types. This increased height from the crossarm to the line conductor affords greater insurance against bird troubles.

Since the length of the puncture path is equal to the flashover distance and has in series at its live end a wall of porcelain of full thickness, this type is inherently free from puncture. The internal air path is a region of negligible dielectric stress.

Radio tests cited in Table I indicate a maximum flux density of very low concentration at the tie wire. The stress in the porcelain adjacent is still lower and the relative degree of freedom from dielectric stress in the porcelain also may be measured by the same figure of merit L/C_p or directly by the lowest voltage for radio effect. This holds for normal voltages. For pre-flashover voltage the relative concentration is diffused by the appearance of conductive corona.

Resistance of this type to flashover initiated by dirty leakage surface is a matter of experience in many extreme cases of contaminated atmosphere. It is this quality that has chiefly recommended the "fog type." The extra height of this type makes it possible to have a long uniform leakage path by the use of many small corrugations on the outside of the insulator. By the elimination of the long dry internal portion of the leakage path from the fog type pin-supported insulator it is possible to extend the same effective style of corrugated leakage surface all the way to the ground terminal. Electrical advantages result from these many small flanges since they cause splashing of rain water, to wet and wash the entire external surface regularly. This makes it unnecessary to wash the insulators in most cases even where atmospheric contamination is severe.

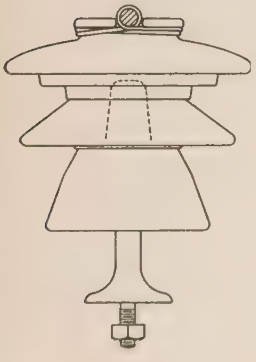
Fig. 4. Pin type insulator; 66-kv rating

Mechanical Characteristics

Mechanically, these small, closely spaced corrugations surrounding the main body of the insulator act as circular reinforcement flanges to strengthen the porcelain wall. They provide non-resonant buffer material to break the shock of any crushing blow and so to prevent an impact from cracking the main wall. Petticoats are so proportioned that these corrugations will break away clean and not propagate the cracks into the main body. The breakage of a corrugation or 2 has a negligible effect in reducing the electrical or mechanical reliability of the support. The fact that the lower end of the porcelain is surrounded and protected by the metal base, removes the open bell effect and eliminates vulnerability at this point. The base produces external compressive forces on the hollow porcelain, consolidating the heavy wall at the bottom. There are no internal parts to cause possible bursting strains. Since the design is ideally adapted to manufacture in one piece, it can be free from the problems of articulated porcelain and metal parts. Testing and assembly follow routine methods and are free from delicate precautions usually considered necessary in conventional types.

Mechanically these porcelain posts are strong and far more rigid than equivalent pin supported insulators. It is possible to produce designs to meet any likely requirements for cantilever strength and rigidity. When fitted with a switch type cap, the post has equal strength upright or inverted.

Merits of the New Insulator

An attempt has been made in this paper to evaluate the merits of this insulator with reference to primary modern requirements for general use on transmission lines on an engineering and test basis. In the past it has been considered necessary to form final judgment of a new insulator only after several years field experience. At present 2 years successful operation are reported on a conventional tie head line post insulator.

Grid Controlled Rectifiers and Inverters

The rectifier and inverter characteristics of the grid controlled mercury arc rectifier of the 6-phase and 12-phase types are considered in this paper. The analysis of rectifier circuits has been extended to cover the effect of grid control on the output voltage, power factor, efficiency, wave forms, and other characteristics; and the characteristics of the grid controlled rectifier operating as an inverter have been determined. Several schemes for applying these rectifiers to railway electrification requiring regeneration are considered.

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IN THE past few years the mercury arc rectifier has come into general use as a means for changing power from alternating current into direct current. The advantages of the rectifier over other types of conversion apparatus, due to its desirable structural features and operating characteristics, have led to the development of rectifier units of high capacity. As an integral part of this development, the design of control grids has also been perfected so that high capacity rectifiers with grids which are suitable for applications requiring grid control are now available.

The field for applications of the mercury arc rectifier is considerably enlarged by the use of control grids. Grids provide a simple means for controlling the rectifier output voltage so that the rectifier will have voltage characteristics similar to those of a d-c generator with field control. Such a controlled unit has a variety of industrial uses. Also, by reversing the d-c connections and providing suitable excitation to the grids, the rectifier tank may be operated as an inverter for changing power from direct to alternating current. Other applications making use of various combinations of rectifier and inverter operation have been suggested.

In order to determine the suitability of the mercury arc rectifier for the various applications, it is essential that its operating characteristics and limitations be known. This paper covers some of the principal characteristics of the mercury arc rectifier when functioning with grid control. The theory of rectifier circuits, which has been presented in numerous papers and books[1-10] for the case of the simple rectifier, is here extended to the grid controlled rectifier by the introduction of the grid control angle as an additional factor.

The characteristics of a simple inverter have been determined by the same method of analysis as is used for the grid controlled rectifier. The equations are similar in form and the regulation characteristics are the same. A number of conditions not required in the case of the rectifier must be met in order to operate as an inverter. These arise as a result of the commutation processes taking place during inversion. An analysis of these requirements has been made from the equations.

A part of this paper covers the application of the grid controlled rectifier-inverter unit to railway electrification where regenerative braking is required and discusses the operating characteristics of such a unit.

Part I—The Grid Controlled Rectifier

It is well known that the output voltage of a rectifier may be controlled by means of grids. Also, that the grids function through their ability to control the time at which the anodes may fire, and that by means of the grids the anode firing may be postponed so that the anode current flows at a time when the anode voltage is reduced. However, there has been no general treatment covering the voltage, power factor, efficiency, wave forms, and other characteristics of a rectifier with grid control. The effect of grid control upon each of these factors will be considered; also the additional duty imposed upon the rectifier by the use of grid control.

This paper will be limited to a consideration of those rectifier circuits having a highly inductive d-c circuit so that the instantaneous output current is essentially constant and the anode current waves

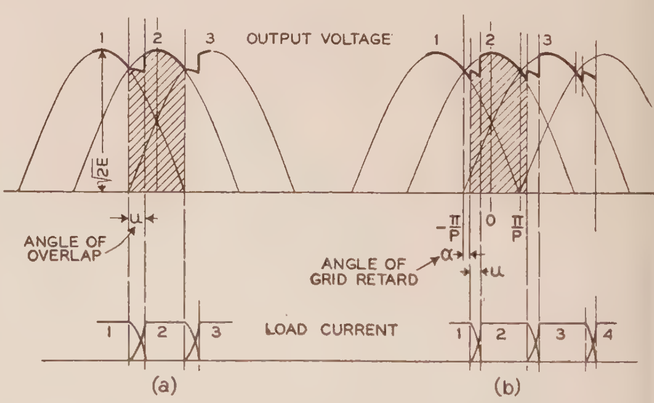


Fig. 1. Output voltage and current waves

(a) Six-phase rectifier without grid control
(b) Six-phase rectifier with grid control

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 20, 1934; released for publication March 26, 1934. *Not published in pamphlet form.*

1. For all references see list at end of paper.

are flat topped. This is the most important case, being the type of circuit most frequently encountered in practice.

Output Voltage

In Fig. 1 (a) are shown the d-c voltage and current waves of a 6-phase rectifier of the usual type without grid control, while Fig. 1(b) shows those for a grid-controlled rectifier.

It has been shown[1,2] that the net output voltage of a rectifier without grid control is given by the expression

$$E_d = \sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p} - \frac{IXp}{2\pi} - E_{\text{arc}} - \frac{W_t}{I} \qquad (1)$$

where the first term represents the d-c voltage at no load, the second term is the voltage drop due to transformer reactance (overlap), and the third and fourth terms are the rectifier arc drop and the transformer winding resistance drop, respectively,
and where

E_d = d-c voltage
E = effective value of transformer secondary voltage to neutral

p = number of secondary phases in each group;
also defined $p = \dfrac{360 \text{ deg}}{\text{degrees conducting period-degrees overlap}}$
I = load current in each group of secondary windings
X = commutating reactance from anode to neutral
E_{arc} = rectifier arc drop
W_t = transformer resistance loss in each group of secondary windings.

In order to facilitate frequent reference to the d-c voltage obtained at no load without grid control, the expression

$\sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p}$ will be denoted by the symbol E_{do}.

When the rectifier firing is postponed by the angle α by means of grid control, as shown in Fig. 1(b), the d-c output voltage is reduced. If it is assumed that the rectifier is operating at no load, that is, that the angle of overlap u is zero, and if the rectifier arc drop and transformer winding resistance drop are neglected, the d-c voltage with grid control is

$$E_d = \frac{\displaystyle\int_{-\frac{\pi}{p}+\alpha}^{\frac{\pi}{p}+\alpha} \sqrt{2}\, E \cos \omega t \, d\omega t}{\displaystyle\int_{-\frac{\pi}{p}+\alpha}^{\frac{\pi}{p}+\alpha} d\omega t} = \sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p} \cos \alpha \qquad (2)$$

If this expression is substituted for the no load term in eq 1 the net output voltage of a grid controlled rectifier is obtained.

$$E_d = \left[\sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p}\right] \cos \alpha - \frac{IXp}{2\pi} - E_{\text{arc}} - \frac{W_t}{I} \qquad (3)$$

The arc drop E_{arc} is the same with or without grid control as it depends only upon the load current passing through the rectifier. The voltage drop $\frac{W_t}{I}$ due to the transformer copper losses may usually also be considered to be the same, though the transformer copper losses are changed to a small extent by the variation in the angle of overlap with grid control. At first sight it is not evident that the voltage drop due to transformer reactance, that is, overlapping, is not changed with grid control. However, the truth of this statement may be verified by the analysis which follows.

Calculating the output voltage on the assumption that u is not zero, we obtain from Fig. 1(b)

$$E_d = \frac{\displaystyle\int_{-\frac{\pi}{p}+\alpha}^{-\frac{\pi}{p}+\alpha+u} \sqrt{2}\, E \frac{\left[\cos\left(\omega t + \frac{2\pi}{P}\right) + \cos \omega t\right]}{2} d\omega t}{\displaystyle\int_{-\frac{\pi}{p}+\alpha}^{\frac{\pi}{p}+\alpha} d\omega t} + \frac{\displaystyle\int_{-\frac{\pi}{p}+\alpha+u}^{\frac{\pi}{p}+\alpha} \sqrt{2}\, E \cos \omega t \, d\omega}{\displaystyle\int_{-\frac{\pi}{p}+\alpha}^{\frac{\pi}{p}+\alpha} d\omega t}$$

$$= \sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p} \left[\frac{\cos \alpha}{2} + \frac{\cos (u + \alpha)}{2}\right] \qquad (4)$$

In order to show that this is equivalent to the first 2 terms of eq 3 it will be necessary to analyze the commutation process.

The transfer of current from one anode to the succeeding anode of the same group takes place during the overlapping or commutating period denoted by u [Figs. 1(a) and 1(b)]. The angle of overlap for a rectifier without grid control is given by the relation[1,3]

$$\cos u = 1 - \frac{IX}{\sqrt{2}\, E \sin \frac{\pi}{p}} \qquad (5)$$

When the firing of the anodes is retarded by the grid control, the angle of overlap is reduced because a higher voltage is available for forcing commutation. An expression for the angle of overlap with retarded firing similar to the above relation may be derived from an analysis of the commutating circuit.

Referring to Fig. 1(b), during commutation from anode 1 to anode 2, a circulating current is set up in the loop formed by these 2 anodes and their connected transformer windings. This current flows as a result of the voltage difference between the 2 phases. The value of the voltage available for commutation is

$$2\sqrt{2}\, E \sin \frac{\pi}{p} \sin (\omega t + \alpha)$$

where time $t = 0$ is taken as the instant at which commutation begins. As a result of the inductance of the transformer windings a voltage is induced in the commutation circuit opposing the transfer of current. This induced voltage is equal and opposite to the commutating voltage. Applying Kirchoffs' second law to the closed loop forming the commutating circuit

$$L \frac{di_2}{dt} = \sqrt{2}\, E \sin \frac{\pi}{p} \sin (\omega t + \alpha) \qquad (6)$$

in which L is the inductance of the circuit between anode and neutral and i_2 is the instantaneous current in anode 2.

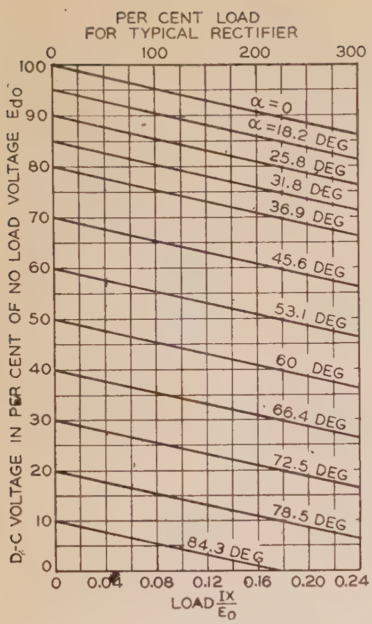
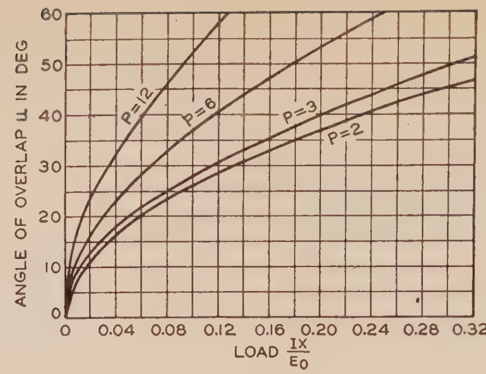


Fig. 2. Voltage regulation characteristics of 6-phase and 12-phase grid controlled rectifiers with interphase transformers ($p=3$) and highly inductive d-c circuit

α = angle of grid retard



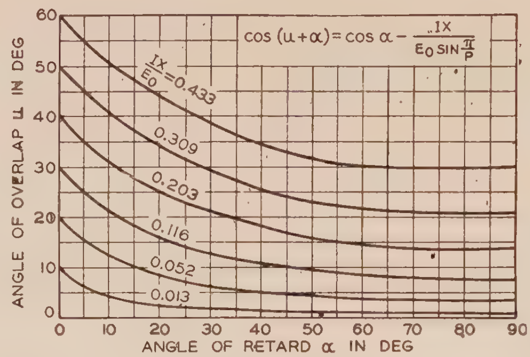


Fig. 3 (above). Angle of overlap for rectifiers without grid control plotted as a function of load

Fig. 4 (below). Variation in angle of overlap with the angle of grid retard for a grid controlled rectifier ($p=3$)

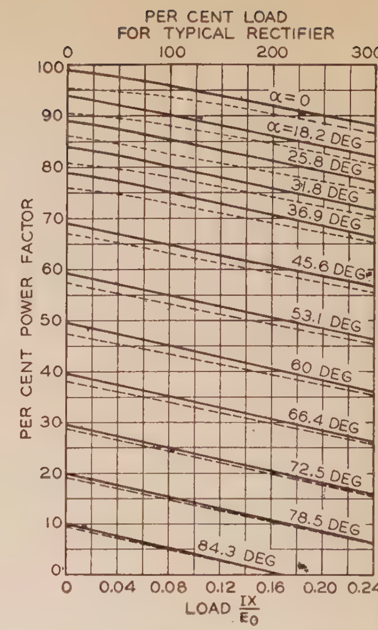


Fig. 5. Power factor characteristics of 6-phase and 12-phase grid controlled rectifiers with $p=3$ and highly inductive d-c circuit

Solid lines—power factor of 12-phase rectifier
Dash lines—power factor of 6-phase rectifier
α = angle of grid retard

Integrating the above equation and substituting $i_2 = 0$ at time $t = 0$, we obtain

$$i_2 = \frac{\sqrt{2}\,E \sin\frac{\pi}{p}}{X}\left[\cos\alpha - \cos(\omega t + \alpha)\right] \tag{7}$$

where $X = L\omega$

Upon the completion of commutation $\omega t = u$ and $i_2 = I$. Then the angle of overlap with grid control is given by[4]

$$\cos(u+\alpha) = \cos\alpha - \frac{IX}{\sqrt{2}\,E\sin\frac{\pi}{p}} \tag{8}$$

It will be noted that this equation is of the same form as eq 5 for the simple uncontrolled rectifier and that it reduces to eq 5 when $\alpha = 0$. Equation 4 may be reduced to the form of eq 3 by substituting the value of $\cos(u + \alpha)$ given by eq 8.

The drop in d-c voltage due to overlapping of anodes arises from the inductive voltage produced by the commutating current.

The instantaneous inductive voltage drop e_L is

$$e_L = L\frac{di_2}{dt}$$

The average d-c voltage drop due to overlapping, ΔE_d, may be calculated by integration of the inductive voltage drop e_L over the angle u

$$\Delta E_d = \frac{1}{2\frac{\pi}{p}}\int_0^u e_L\, d\omega t$$

Substituting the values of e_L from eq 6 this becomes

$$\Delta E_d = -\sqrt{2}\,E\frac{p}{\pi}\sin\frac{\pi}{p}\left[\frac{\cos(u+\alpha) - \cos\alpha}{2}\right] \tag{9}$$

The replacing the bracketed terms by $-\dfrac{IX}{\sqrt{2}\,E\sin\frac{\pi}{p}}$ from eq 8 we obtain

$$\Delta E_d = \frac{IXp}{2\pi} \tag{10}$$

This relation shows that the voltage drop due to transformer reactance (overlapping) is independent of the use of grid control.

The d-c voltage regulation characteristics of a grid controlled rectifier, calculated by means of eq 3, are shown graphically on Fig. 2. The voltage drops due to arc drop and resistance drop are not included in these curves. A constant grid retard, angle α, is assumed for each curve. Values of α are chosen so that the reduction in d-c voltage at no load, that is, $\cos\alpha$, varies in steps of 5 and 10 per cent of the voltage at no load without grid control.

The curves on Fig. 2 apply to either 6-phase or 12-phase rectifiers with interphase transformers giving double wye or quadruple zigzag operation, that is, where $p = 3$. The load is expressed in terms[5] of $\dfrac{IX}{E_0}$ where I and X have the same values as in eq 1 and $E_0 = \sqrt{2}\,E$.

Calculation of Angle of Overlap

The angle of overlap of a rectifier without grid control is given by eq 5. In Fig. 3 is shown the

overlap plotted as a function of load $\frac{IX}{E_0}$ for different types of rectifiers having various values of p.

When the anode firing is retarded by grid control the angle of overlap may be determined from eq 8. The variation in the angle of overlap with the angle of grid retard for a grid-controlled rectifier is shown by Fig. 4. These curves apply to rectifiers operating with interphase transformers so that $p = 3$.

Power Factor

The effective value of the a-c line current to a rectifier is directly proportional to the d-c output current (neglecting the effect of overlap) and is determined by the transformer connections. When the anode firing is retarded the line current is caused to lag in phase, but its value remains substantially the same. As the a-c line voltage is usually practically constant, the primary kilovoltampere input to a rectifier does not change appreciably as the d-c voltage is varied by grid control, the d-c current being held constant. This means that the rectifier output voltage is varied at the expense of a-c line power factor and that the power factor is approximately equal to the ratio of the d-c voltage with grid control to the voltage which would be obtained without grid control.

It has been shown[6] that the power factor of a rectifier without grid control may be expressed by the general equation

$$\text{Power factor} = K \frac{\cos^2 \frac{u}{2}}{\sqrt{1 - Cf(u)}} \qquad (11)$$

where constants K and C are characteristic of the type of connection used and $f(u)$ is a function of the

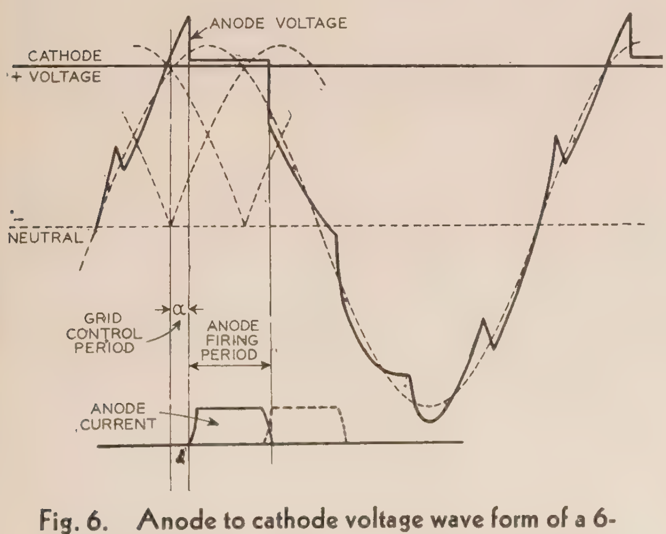


Fig. 6. Anode to cathode voltage wave form of a 6-phase grid-controlled rectifier without interphase transformer

angle of overlap. A similar equation has been derived for the power factor of a grid controlled rectifier (see appendix A of this paper). This equation has the form

$$\text{Power factor} = K \frac{\frac{1}{2}[\cos \alpha + \cos (u + \alpha)]}{\sqrt{1 - Cf_1 (u, \alpha)}} \qquad (12)$$

where constants K and C have the same values as in eq 11 and $f_1 (u, \alpha)$ is a function of both the angle of overlap and the angle of retard. The term $\frac{1}{2}$ [cos α + cos $(u + \alpha)$] is the ratio of the d-c voltage under load with grid control E_d (neglecting arc drop and resistance drop) to the d-c voltage at no load without grid control, E_{do}. Expressing the power factor in terms of the ratio of these 2 voltages we obtain

$$\text{Power factor} = K \frac{\frac{E_d}{E_{do}}}{\sqrt{1 - C f_1 (u, \alpha)}} \qquad (13)$$

For a 6-phase rectifier of the usual type this equation becomes

$$\text{Power factor} = 0.955 \frac{\frac{E_d}{E_{do}}}{\sqrt{1 - 3 f_1 (u, \alpha)}} \qquad (14)$$

While for a 12-phase rectifier it is

$$\text{Power factor} = 0.988 \frac{\frac{E_d}{E_{do}}}{\sqrt{1 - 1.61 f_1 (u, \alpha)}} \qquad (15)$$

The values of $f_1 (u, \alpha)$, $\sqrt{1-3 f_1 (u, \alpha)}$ and $\sqrt{1-1.61 f_1 (u, \alpha)}$ may be obtained by referring to Fig. 13 in appendix A of this paper.

The power factors for both 6-phase and 12-phase rectifiers having the regulation characteristics shown on Fig. 2 are given by the curves on Fig. 5. The same values of α have been chosen for both sets of curves so that the power factor corresponding to any voltage regulation curve may be determined directly. The effect of transformer magnetizing current has been neglected in these curves. Also it has been assumed that the arc drop and transformer winding resistance drop constitute a part of the d-c load.

Efficiency

The losses in a rectifier tank equipped with control grids will not be changed appreciably by the use of grid control, the load current remaining the same. There will be a fractional increase in the main transformer losses due to the reduction in the angle of overlap.[7] However, this will usually be so small that it may be neglected. The most important increase in losses will occur in the interphase transformer due to the increase in interphase voltage.

As the interphase transformer constitutes only a minor part of the total losses, it is seen that at a given load current the losses remain practically constant with grid control and that the reduction in the efficiency is only that resulting from the smaller output due to reduction in d-c voltage.

Wave Form

It is apparent from Fig. 1(b) that as the angle of grid retardment is increased, the magnitude of the ripple in the d-c output voltage wave is also increased.

The coefficients of the sine and cosine terms of the harmonics in the output waves are respectively as follows:

$$a_m = \frac{E_{do}}{2} \cos m\pi \left[\frac{\sin (mp' + 1)(u + \alpha) + \sin (mp' + 1)\alpha}{mp' + 1} - \frac{\sin(mp' - 1)(u + \alpha) + \sin(mp' - 1)\alpha}{mp' - 1}\right] \quad (16)$$

$$b_m = \frac{E_{do}}{2} \cos m\pi \left[\frac{\cos (mp' + 1)(u + \alpha) + \cos (mp' + 1)\alpha}{mp' + 1} - \frac{\cos (mp' - 1)(u + \alpha) + \cos (mp' - 1)\alpha}{mp' - 1}\right] \quad (17)$$

The effective values of the various harmonics are then

$$h_m = \frac{1}{\sqrt{2}} \sqrt{a_m^2 + b_m^2}$$

where m has values 1, 2, 3, 4, etc., p' is defined as the number of secondary phases, a_m = coefficient of sine term of the harmonic of the order mp and b_m = coefficient of cosine term of the harmonic of the order mp.

The wave form of the primary line current is also affected by the retardment of anode firing. However, in this case the effect is only that due to the shortening of the angle of overlap. As the amount the grid is retarded is increased and the angle of overlap becomes shorter, the primary current wave form approaches that for the case of no load where there is zero overlap.

Duty on Rectifier

When the output voltage of a 6-phase rectifier is controlled by means of grids, the voltage on the anodes has the wave form shown on Fig. 6.

It will be noted that the anode voltage wave differs from that of a rectifier without grid control in 2 important respects. First, during the control period, indicated by the angle α, the anode voltage is positive by an amount greater than the arc drop voltage although the anode carries no current. The second effect of grid control is to increase the rate of rise of inverse voltage on the anode. This is indicated by the part of the curve immediately following the firing period. Both of these effects increase the duty on anodes and grids over that imposed when operating as a rectifier without grid control.

Part II—The Inverter

A grid controlled mercury arc rectifier may be operated as an inverter by reversing the d-c connections and providing suitable excitation voltage to the grids.[8] The connection diagram for a 6-phase inverter is shown on Fig. 7(a). The operation of an inverter having a highly inductive d-c circuit may be understood by reference to Fig. 7(b) which shows the voltage and current wave shapes.

The conversion of power from a d-c system to an a-c system requires that the rectifier anodes carry current when the transformer secondary voltages are negative, that is, that the anode currents flow in opposition to the voltages from the a-c system. In the inverter this is accomplished by controlling the anode firing by means of the grids.

Referring to Fig. 7, anode 1 carries current during

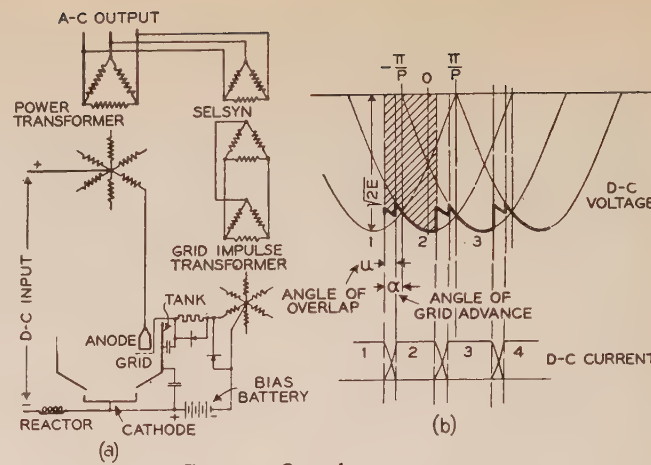


Fig. 7. Six-phase inverter

(a) Connection diagram
(b) Current and voltage waves

the time that its transformer voltage is negative. The other anodes are prevented from firing by exciting their grids with a negative voltage. The transfer of current from anode 1 to anode 2 is initiated by exciting the grid of anode 2 positively. Commutation must be started while the counter electromotive force in the transformer winding connected to anode 2 is less than that in the winding connected to anode 1. The counter electromotive force *voltage difference* in the circuit made by these 2 anodes forces the transfer of current from anode 1 to anode 2 and overcomes the commutating impedance of the transformer windings. The total current in the d-c system is maintained substantially constant during commutation by means of a reactor in the d-c line. In order that the current be commutated successfully, it is necessary that the firing of anode 2 be initiated early enough so that commutation is completed before the anode voltages equalize. Referring to Fig. 7(b), this means that the angle of grid advance α must always be greater than the angle of overlap u. This commutation requirement is a basic difference between the grid controlled rectifier and the inverter.

It is evident that in order that this type of inverter be practical, the operating conditions must be such that successful commutation is assured at all times. If commutation is not completed, the inverter will draw a short-circuit current from the d-c system. In order to determine the effect of commutation requirements upon operating characteristics, an analysis was made of the commutating conditions in an inverter.

Voltage Characteristics

The relation between the a-c and d-c voltages for an inverter may be expressed by an equation similar to that which was derived for the voltage relations of a grid controlled rectifier. In the case of the inverter, the voltage drops, due to (1) overlapping, (2) rectifier arc drop, and (3) transformer winding resistance drop, add to the d-c voltage which would appear at no load instead of subtracting as in the case of the rectifier, since the direction of current flow is

reversed with respect to the d-c voltage when inverting. The voltage equation for the inverter is

$$E_d = \left[\sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p}\right] \cos \alpha + \frac{IXp}{2\pi} + E_{arc} + \frac{W_t}{I} \tag{18}$$

Where α is the angle of grid advance [Fig. 7(b)], and the other terms have the same values as for eq 3.

The first and second terms in eq 18 may be derived in the same manner as the corresponding term in eq 3 for the rectifier. The relation between these equations will be seen by a comparison of Figs. 1(b) and 7(b). Referring to these figures, if the angle of overlap u is zero, the d-c voltage will be the same in both cases and will have the value $\sqrt{2}\, \frac{P}{\pi} \sin \frac{\pi}{p} \cos \alpha$, where α is the angle of retard for the rectifier and the angle of advance for the inverter. Overlapping causes the anode firing to be delayed in phase, which tends to lower the d-c voltage of the rectifier and raise the d-c voltage of the inverter. The rectifier d-c voltage drop due to overlapping is given by eq 10. It will be noted that this voltage drop depends only upon the current to be commutated and the commutating reactance and remains the same regardless of the time at which commutation occurs and the length of the overlap period. Therefore, it will have the same value for the inverter as it does in the case of the rectifier.

The voltage regulation characteristics for this inverter are shown on Fig. 8. These curves apply to both 6-phase and 12-phase inverters with interphase transformers ($p = 3$). The voltage drops due to arc drop and resistance drop have been neglected and only the voltage drop due to overlap has been considered. Also, the d-c circuit is assumed to be highly inductive so that the instantaneous input current is essentially constant.

These regulation curves are based on the assumption that the a-c voltage is held constant. The d-c voltage is expressed in per cent of the maximum d-c voltage at which the inverter might operate

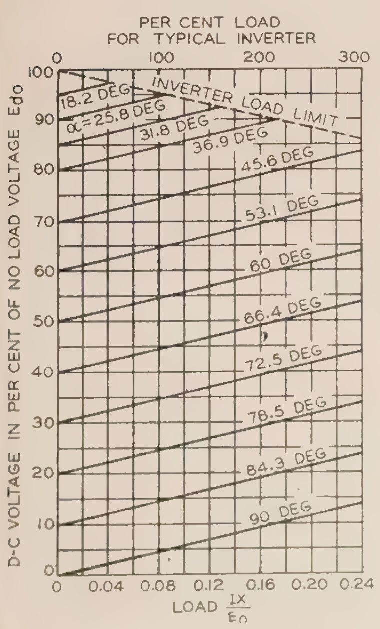


Fig. 8. Voltage regulation characteristics of 6-phase and 12-phase inverters with p = 3 and highly inductive d-c circuit

α = angle of grid advance

assuming no overlap and no grid advance. This voltage is equal to the no load voltage of a rectifier without grid control and is $E_{do} = \sqrt{2}\, E \frac{p}{\pi} \sin \frac{\pi}{p}$.

The manner in which the inverter load is determined may be understood from the regulation curves. Assume, for example, that the inverter is connected to the a-c system with the grid excitation advanced 36.9 deg (Fig. 8). If a low voltage is applied on the d-c side and gradually increased, the inverter will not pick up load until the d-c voltage attains a value of 80 per cent. That is, the inverter will not pick up load until the impressed d-c voltage becomes greater than the d-c counter electromotive force generated in the inverter by the a-c voltages. If it is desired to invert with a low d-c voltage, less than 80 per cent for example, the grid excitation must be advanced until the counter electromotive force becomes less than the impressed voltage. As the impressed d-c voltage is increased after the inverter has picked up load, the load carried will be determined by the regulation curve for the particular grid setting which is used. The load may be increased, by raising the d-c voltage, until the inverter fails to commutate, as will be explained later under "Commutation and Load Limits."

Calculation of Angle of Overlap

The commutation processes of this type of inverter may be analyzed in the same manner as those of the grid-controlled rectifier. The voltage equation for the commutating circuit of the inverter is

$$L \frac{di_2}{dt} = -\sqrt{2}\, E \sin \frac{\pi}{p} \sin (\omega t - \alpha) \tag{19}$$

Solving this equation, the angle of overlap when inverting is given by the relation

$$\cos (u - \alpha) = \cos \alpha + \frac{IX}{\sqrt{2}\, E \sin \frac{\pi}{p}} \tag{20}$$

In Figure 9 is shown the variation in the angle of overlap with the angle of grid advance for an inverter.

Commutation and Load Limits

It has been pointed out that the angle of advance of the grid excitation for this type inverter must always be greater than the angle of overlap in order that commutation be completed successfully. This requirement limits the load which may be carried and also affects the voltage relations between the a-c and d-c systems.

The load limit of the inverter, as fixed by commutation requirements, may best be expressed in terms of the voltage relations. Let it be assumed that an inverter is operating with a fixed angle of grid advance. As the load current is increased the angle of overlap increases until finally at the limiting load for this grid setting, assuming no time is required for deionization, the angle of overlap is just equal to the angle of advance. When the inverter is operating under these limiting conditions the angle

of overlap will be the same as that when rectifying an equal load with the grids not retarded, and the voltage wave forms will be similar, and the d-c voltages will be equal (neglecting arc drop and resistance drop). The load limiting curve for the

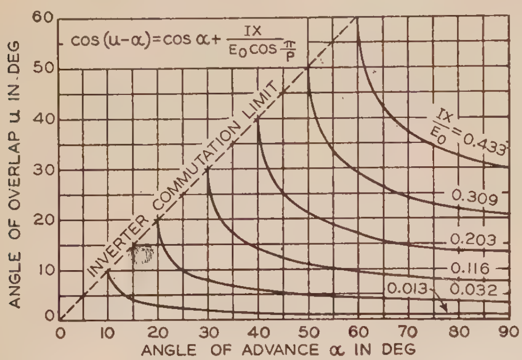


Fig. 9. Variation in angle of overlap with the angle of grid advance for an inverter (p=3)

inverter is therefore the same as the voltage regulation curve for the rectifier with the grids not retarded. The inverter load limit is shown by the dotted curve on Fig. 8.

These considerations show that in order to invert, the a-c d-c voltage relations, the load, and the angle of advance must all be properly adjusted to each other. It is seen that in order to increase the load limit the grid angle must be advanced to compensate for the increasing angle of overlap and obtain sufficient time for commutation and deionization. However, it should be noted particularly that the inverter will not operate when the d-c voltage is greater than that which would be obtained when operating as a simple rectifier at the same load current without grid control.

These requirements have been verified by test on an experimental 6-phase inverter of the type described. In order to make the inverter operate it was found necessary to reduce the d-c voltage to a value less than that obtained when operating as a rectifier without grid control, the a-c voltage remaining constant.

The voltage required for commutation of this type inverter is supplied by the a-c system. In order to operate, the inverter must be connected to an a-c system capable of supplying this voltage and carrying the commutating current. It will not operate when connected to a pure resistance a-c load.

Wave Forms

The current and voltage wave forms of the inverter are very nearly the same as those of the grid controlled rectifier when both are operated at the same d-c voltage and current.

Power Factor

Since commutation of the anode currents must be completed before the anode voltages become equal (see Fig. 7(*b*)), the anode current waves will always be earlier in phase than the voltage waves. Corresponding currents will flow on the other side of the transformer and therefore the currents in the a-c line will always lead the a-c line voltages and the inverter will deliver power only at a leading power factor.

From a study of the commutation requirements it has been shown that an inverter of this type which is commutated from the a-c system must always operate at leading power factor. The power factor of the inverter may be expressed by equations similar to those for the rectifier. (Refer to appendix B of this paper.) These equations have the form:

$$\text{Power factor} = K\,\frac{{}^1/_2[\cos\alpha + \cos(u-\alpha)]}{\sqrt{1 - C\,f_2(u,\alpha)}} \tag{21}$$

For a 6-phase inverter this equation becomes:

$$\text{Power factor} = 0.955\,\frac{\frac{E_d}{E_{do}}}{\sqrt{1 - 3\,f_2(u,\alpha)}} \tag{22}$$

While for a 12-phase inverter it is

$$\text{Power factor} = 0.988\,\frac{\frac{E_d}{E_{do}}}{\sqrt{1 - 1.61\,f_2(u,\alpha)}} \tag{23}$$

The power factors for both a 6-phase and a 12-phase inverter are given on Fig. 10. These power factors are given for the same values of grid advance as chosen for the regulation curves shown on Fig. 8.

Duty on Rectifier

The anode voltage when inverting will have a wave form similar to that shown by Fig. 11. This curve shows that the anode voltage is always positive except during the small interval allowed for deionization. The grid must acquire control of the anode during this small interval.

It is evident by comparison of the anode voltages that the duty on the grids is much greater in the case of the inverter; first, only a short period is available for deionization and the grid must acquire control of the anode during this interval; second, the grids must function to prevent anode firing during practically the entire inactive period of the anode; and third, the anode must pick up immediately when its grid acquires a positive potential. This last requirement means that the excitation arc must be properly located and must furnish adequate ionization to insure good pick-up of the main anodes at all loads. Since the anode firing period is always only a fractional part of a cycle the grid voltage wave must be negative during most of the cycle. This may be accomplished either by means of a negative bias or by using an impulse voltage for exciting the grids.

Part III—Application of the Unit to Railway Electrifications With Regenerative Braking

The use of mercury arc rectifiers capable of inverting has been proposed for d-c railway electrifications where regenerative braking is required. In the past such electrification systems have mostly used motor-

generator equipment. The motor-generator set will receive power from the d-c system and transfer it to the a-c system when the d-c voltage rises. No other changes are necessary. However, in the case of the rectifier, it is necessary to reverse the d-c leads in order to change from generation to regeneration. This means that the d-c circuit must be opened and closed in order to change over. At the same time the grid excitation and the main d-c a-c voltage relations must be adjusted properly in order to insure commutation when inverting.

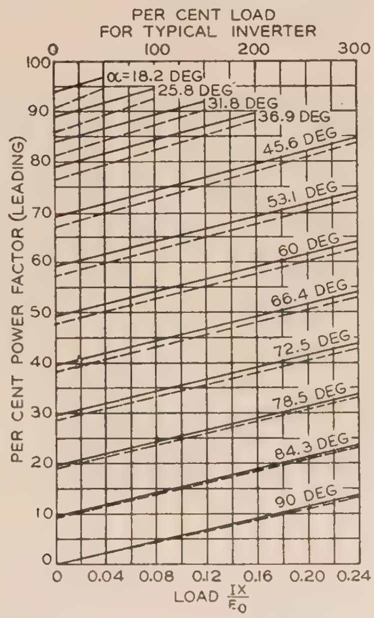
Because of the many differences between the operating characteristics of motor-generator equipment and those of regenerative rectifier equipment a careful study has been made of the requirements which must be met in railway applications.

Railway Service Requirements

In practical railroad operation where regenerative braking is employed, the substation must be able to deliver or to receive power as determined by the performance of trains on the road. Regeneration by a train is always initiated by the locomotive engineer, who decides when it should be done and makes the necessary changes to accomplish it. The substation equipment or the substation operator has no knowledge of the engineer's decision until the locomotive is already regenerating. The demand for the substation to receive regenerated power appears first in the form of an increase in the d-c bus voltage at the substation.

Fig. 10. Power factor characteristics of 6-phase and 12-phase inverters with p=3 and highly inductive d-c current

Solid lines — power factor of 12-phase inverter
Dash lines — power factor of 6-phase inverter
α = angle of grid advance



Limitations of Rectifier-Inverter Equipment

Because of the changes which must be made in order to change a rectifier tank from rectifier to inverter operation, and *vice versa*, it is seen that a single tank rectifier inverter-unit cannot be expected to float from generation to regeneration easily and inherently like a synchronous motor generator set. It is also evident that some time element is involved in changing the rectifier from one type of operation to the other and that during this time it will be disconnected from the substation bus.

A single rectifier operating with one connection will neither invert itself inherently nor give a reliable indication of the necessity for reversal. For example, assume that the rectifier has been generating and that the railway load changes so that regenerating operation is required. Then the rectifier will simply go to no load and remain at no load until the railway load again requires power for motoring operation. The rectifier will not allow any reverse current to flow and so no indication of the necessity for reversal can be obtained by means of a reverse current relay or other indicating devices of that type. Should a single rectifier tank be operating as an inverter, upon the cessation of regeneration and the recurrence of motoring demand, the conditions will be the same as those just cited.

Proposed Arrangements of Rectifier-Inverter Equipment for Regeneration

In order to meet the requirements for operation in railway service and to overcome the above limitations of the rectifier equipment, a number of different arrangements have been proposed. Some of these schemes will be described in the following paragraphs, together with a description of their operating characteristics. However, no attempt will be made to determine the relative merits of the different schemes.

One scheme which has been proposed uses a single rectifier tank for rectifying and inverting, the d-c connections being reversed when changing from one type of operation to the other. In order to obtain an indication of the necessity for reversal of connections when a single rectifier tank is used, the use of either a relay equipment consisting of a low ca-

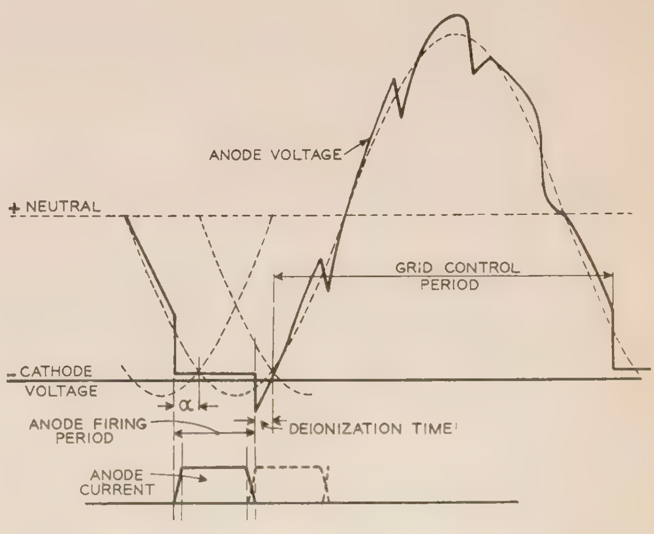


Fig. 11. Anode to cathode voltage wave form of a 6-phase inverter without interphase transformer

pacity rectifier and inverter permanently connected, or of a small synchronous motor generator set floating on the d-c bus has been suggested. By using the latter of these 2 devices, the small motor generator set, a means may also be provided for commutating the inverter in case of failure of the a-c system voltage.

The d-c voltage characteristics of a single tank unit taking into account the effect of rectifier arc drop are shown by Fig. 12. From these curves it will be noted that if the grid excitation angle is held constant both when rectifying and when inverting and the proper angle is chosen for each condition, shunt voltage characteristics such as those of curves aa' and bb' will be obtained. In order that the inverter carry the required loads, the angle of grid advance must be large enough to provide time for commutation and deionization at the maximum inverting load, with a safe margin to assure reliability.

The necessity for reversing d-c connections may be eliminated by using a double tank unit, one tank being connected always as a rectifier and the other as inverter. Such a double unit will have shunt voltage characteristics similar to those of the d-c machine of a motor generator set and will permit a smooth and automatic reversal of power flow.

The fact that the inverter will deliver a-c power only at a leading power factor is not expected to prove a serious disadvantage to its use for railway electrification. As the power factor of the inverter is substantially the same as that of the rectifier when the grid excitation angles are equal, except that it is leading instead of lagging, the reactive kilovolt-ampere load which must be carried by the a-c system remains approximately the same for a given load whether rectifying or inverting. Stated in other words, only the flow of real power reverses direction when the operating conditions are changed from rectification to inversion or *vice versa*. The conditions are similar to those for an induction motor operating as a generator.

Part IV—Other Applications of the Grid Controlled Mercury Arc Rectifier

The use of combinations of the rectifier and inverter for constructing frequency changers and d-c transformers has also been proposed. If a rectifier and inverter are connected in series, power may be transferred from one a-c system to another of different frequency. When the rectifier and inverter are connected in the reverse order power may be transferred from one d-c system to another of different voltage. The use of the inverter of this type for these applications is seriously restricted by its power factor characteristics. Before the inverter can come into general use for these applications, some means must be devised which will permit operation at lagging power factors.

Frequency changer circuits in which only one rectifier tank is used, the same anodes performing the double function of rectification and inversion have also been proposed. However, up to the present time these circuits have not proved generally practical for use with a 60-25 cycle ratio of frequency transformation.

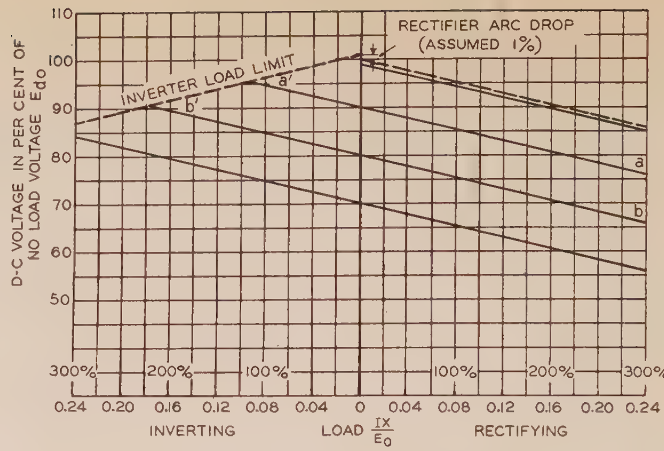


Fig. 12. Voltage regulation characteristics of a rectifier-inverter unit for regeneration

The percentage power factor is approximately the same as the percentage d-c voltage for a 12-phase unit (see Figs. 2 and 5) The upper load scale indicates the percentage load for a typical unit

Appendix A—Power Factor of the Rectifier

The effective or root mean square value of the rectifier anode current wave when there is no overlapping is $\frac{I}{\sqrt{p}}$ where I is the maximum value of the flat topped anode wave. When overlapping takes place and the rectifier is operating with grid control, the anode current during the commutating periods may be calculated from eqs 7 and 8 given in Part I of the paper. Combining these equations the anode current during the commutating period at the beginning of the anode current wave is

$$i_2 = I\left(\frac{\cos\alpha - \cos(\omega t + \alpha)}{\cos\alpha - \cos(u + \alpha)}\right) \tag{24}$$

and the anode current during the commutating period at the end of the wave is

$$i_1 = I\left(1 - \frac{\cos\alpha - \cos(\omega t + \alpha)}{\cos\alpha - \cos(u + \alpha)}\right) \tag{25}$$

The heating effect of the anode current wave with overlapping may be determined by integration of the equation

$$I^2_{eff} = \frac{1}{2\pi}\int_0^u i_2^2\, d\omega t + \frac{I^2}{2\pi}\left(\frac{2\pi}{p} - u\right) + \frac{1}{2\pi}\int_0^u i_1^2\, d\omega t$$

substituting the values of i_1 and i_2 the equation becomes [9]

$$I_{eff} = \frac{I}{\sqrt{p}}\sqrt{1 - p\,\frac{1}{\pi}\int_0^u\left[\left(\frac{\cos\alpha - \cos(\omega t + \alpha)}{\cos\alpha - \cos(u + \alpha)}\right) - \left(\frac{\cos\alpha - \cos(\omega t + \alpha)}{\cos\alpha - \cos(u + \alpha)}\right)^2\right] d\omega t} \tag{26}$$

$$I_{eff} = \frac{I}{\sqrt{p}}\sqrt{1 - p\,\mathrm{f}_1(u, \alpha)} \tag{27}$$

where $\mathrm{f}_1(u, \alpha)$ represents the value of the integral in eq 26. Solving the integral we obtain

$$\mathrm{f}_1(u, \alpha) = \frac{1}{2\pi}\left[\frac{\sin u\,(2 + \cos(u + 2\alpha)) - u\,(1 + 2\cos\alpha\cos(u + \alpha))}{(\cos\alpha - \cos(u + \alpha))^2}\right] \tag{28}$$

When $\alpha = 0$ this function reduces to the value obtained by other authors[10] for the rectifier without grid control.

The factor $\sqrt{1 - p\,\mathrm{f}_1(u, \alpha)}$ represents the change in the effective

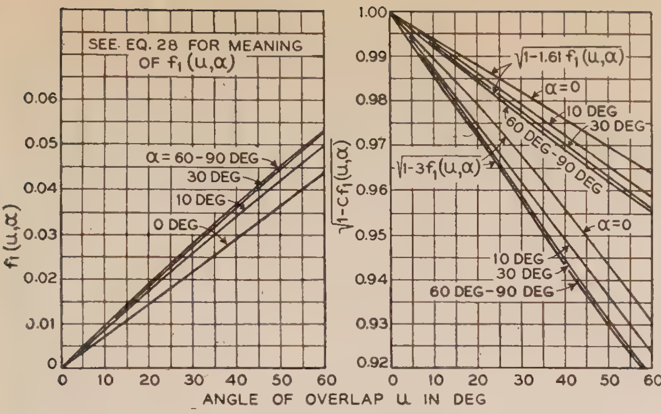


Fig. 13. Curves for grid controlled rectifiers giving the values of $f_1(u, \alpha)$ and $\sqrt{1-Cf_1(u, \alpha)}$ as functions of u for various angles of grid retard

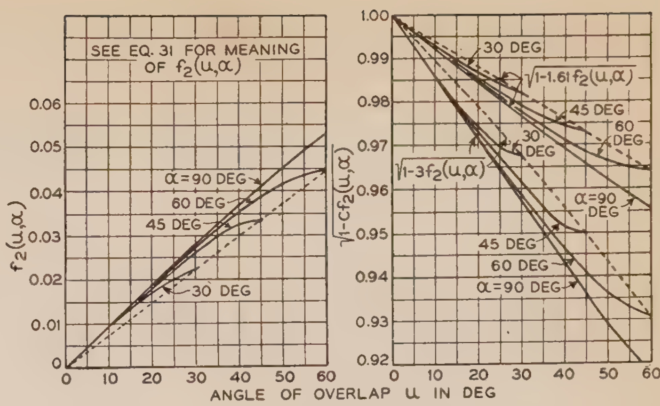


Fig. 14. Curves for inverters giving the values of $f_2(u,\alpha)$ and $\sqrt{1-Cf_2(u, \alpha)}$ as functions of u for various angles of grid advance

value of anode current due to overlapping. A factor of similar form applies to the primary current of the rectifier with overlapping.

The power factor of a rectifier is defined by the ratio, power factor $= \dfrac{\text{power output}}{\text{kilovoltampere input}}$, if the rectifier arc drop and transformer winding resistance drops are assumed to be part of the d-c load. The power factor may be expressed in terms of the various voltage and currents

$$\text{Power factor} = \frac{E_{dc} I_{dc}}{3\, E_L I_L}$$

where

E_{dc} = d-c voltage $\qquad E_L$ = primary line to neutral voltage
I_{dc} = d-c current $\qquad I_L$ = primary line current

The d-c voltage may be expressed in terms of the primary line to neutral voltage by eq 4 and the primary line current may be expressed in terms of the d-c current.

$$E_{dc} = \sqrt{2}\, E_L \frac{P}{\pi} \sin\frac{\pi}{P}\left[\frac{\cos\alpha}{2} + \frac{\cos(u+\alpha)}{2}\right]$$

where $E_L = E$

$$I_L = \frac{I_{dc}}{\sqrt{6}}\sqrt{1 - 3\,f_1(u,\alpha)} \text{ for a 6-phase rectifier}$$

$$I_L = I_{dc}\frac{(\sqrt{3}+1)}{4\sqrt{3}}\sqrt{1 - 1.61\,f_1(u,\alpha)} \text{ for a 12-phase rectifier}$$

Substituting these values we obtain

$$\text{Power factor} = \frac{3}{\pi}\,\frac{\left[\dfrac{\cos\alpha}{2} + \dfrac{\cos(u+\alpha)}{2}\right]}{\sqrt{1 - 3\,f_1(u,\alpha)}} \text{ for a 6-phase rectifier}$$

and

$$\text{Power factor} = \frac{6\sqrt{2}}{\pi(\sqrt{3}+1)}\,\frac{\left[\dfrac{\cos\alpha}{2} + \cos\dfrac{(u+\alpha)}{2}\right]}{\sqrt{1 - 1.61\,f_1(u,\alpha)}} \text{ for a 12-phase rectifier}$$

For convenience in calculating rectifier power factors the values of $f_1(u,\alpha)$, $\sqrt{1-3\,f_1(u.\alpha)}$, and $\sqrt{1-1.61\,f_1(u,\alpha)}$ have been calculated for various values of u and α, and are plotted on Fig. 13.

Appendix B—Power Factor of the Inverter

The effect of overlapping upon the root mean square values of the anode and primary currents of the inverter may be calculated in the same manner as used in appendix A for the rectifier.

The value of the anode current during the commutating period at the beginning of the anode current wave may be shown to be

$$i_1 = I\left(\frac{\cos(\omega t - \alpha) - \cos\alpha}{\cos(u - \alpha) - \cos\alpha}\right) \tag{29}$$

and during the commutating period at the end of the anode current wave

$$i_1 = I\left(1 - \frac{\cos(\omega t - \alpha) - \cos\alpha}{\cos(u - \alpha) - \cos\alpha}\right) \tag{30}$$

Solving an equation which is similar to that for the rectifier, the effective anode current is found to be

$$I_{eff} = \frac{I}{\sqrt{p}}\sqrt{1 - p\,f_2(u,\alpha)}$$

where function f_2 is given by

$$f_2(u,\alpha) = \frac{1}{2\pi}\left[\frac{\sin u\,(2 + \cos(u - 2\alpha)) - u\,(1 + 2\cos\alpha\cos(u-\alpha))}{(\cos(u-\alpha) - \cos\alpha)^2}\right] \tag{31}$$

The equations for the inverter power factor may be derived in the same way as those for the rectifier. The power factor of a 6-phase inverter is

$$\text{Power factor} = \frac{3}{\pi}\,\frac{\left[\dfrac{\cos\alpha}{2} + \dfrac{\cos(u-\alpha)}{2}\right]}{\sqrt{1 - 3\,f_2(u,\alpha)}}$$

and for a 12-phase inverter

$$\text{Power factor} = \frac{6\sqrt{2}}{\pi(\sqrt{3}+1)}\,\frac{\left[\dfrac{\cos\alpha}{2} + \dfrac{\cos(u-\alpha)}{2}\right]}{\sqrt{1 - 1.61\,f_2(u,\alpha)}}$$

The values of $f_2(u,\alpha)$, $\sqrt{1-3\,f_2(u,\alpha)}$, and $\sqrt{1-1.61\,f_2(u,\alpha)}$ for various values of u and α are plotted on Fig. 14.

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Selection and Performance of Suspension Insulators

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Some of the methods used in selecting and checking suspension insulators during the past 15 years on a large electric power transmission system comprising some 3,000 miles of steel tower lines, most of which operate at 132,000 volts, are outlined in this paper. The results obtained through various tests, the use of these results as a guide for insulator selection, and actual performance and expected life of insulators are discussed. A large amount of laboratory and field test data is included, on the basis of which a life expectancy of 50 years for suspension insulators is believed possible.

THE importance of the suspension insulator as a link in the chain of transmission of electric power sometimes has been minimized, if not overlooked, particularly during the past decade or so. Certainly as far as the engineering literature on the subject is concerned, it frequently would appear that the last and final word on the subject had been said; yet it is a fact that frequently a section of transmission involving millions of dollars of expenditure can be put out of commission for anywhere from a minute to possibly several days by the failure of a single disk insulator among the many tens of thousands.

Considering the complex structure of the suspension insulator, it is surprising that a study of the many elements entering into its composition and the assembly of those elements into a single structure has not been pursued with the same thoroughness as has been applied to many structures of a much simpler nature. Admittedly there has been vast improvement in the design and manufacturing processes of insulators in recent years, but it does not follow that a uniformity of the product has been reached that will assure satisfactory operating reliability. Nearly all manufacturers of suspension insulators periodically change details of the design and methods of assembly of their units. This does not always involve a change in catalog numbers, nor is the purchaser always advised that changes have been made. It may be assumed generally that these changes result in an improvement of the product, but occasionally some slight modification will adversely affect the performance of the insulator. This may be apparent from an exhaustive laboratory test, but not always, and it may take several years of field experience to show up the defect. This means that the selection of insulators to give the best results from a complete engineering standpoint, involving cost, performance, and deterioration, is a difficult problem if one attempts to do it with any degree of precision. It is necessary to know not only that the design of the insulator is correct, but also that a uniformity of the product is obtained. For example, insulators manufactured according to the same design, but during different years, may vary in their performance due to some slight change in materials used or in the care taken in the manufacturing processes.

The authors having been connected for the past 15 years with the construction of some 3,000 miles of steel tower transmission lines, most of which operate at 132 kv, in which the selection and installation of some million insulators was involved, and having had the opportunity later to follow the performance of these lines, believe that some of the methods they have used in the selection and checking of insulators may be of interest. In this paper they will outline some of these methods, indicate the results obtained through the various tests, the use made of these results as a guide for insulator selection, and finally discuss the actual performance of the insulators and point out what light on general deterioration and expected life of insulators is thrown by such performance.

On the basis of the data presented the authors have reached the following conclusions:

1. The present A.I.E.E. standard tests for suspension insulators, which are mainly factory acceptance tests, are not in themselves sufficient to furnish a basis for detecting all insulators of inferior design and manufacture, or for comparing competitive makes of insulators.

2. Based on results obtained by tests conducted by the American Gas and Electric Company, laboratory tests can be devised that will furnish a basis for proper selection of insulators and permit the weeding out of insulators of inferior design and manufacture.

3. Field testing of insulators is essential, and when carried on over a sufficiently long period, can serve as a reliable index of the condition, rate of deterioration, and life expectancy of insulators.

4. If proper selection tests are made in advance, the results of such field testing and the life performance and deterioration of insulators can be predicted with a fair degree of accuracy.

5. Modern suspension insulators of proper design and manufacture, properly selected and correctly applied can be expected to give satisfactory performance over a long period of time, possibly to the extent of 50 years.

Normal Routine Factory Tests

Practically all high voltage insulators are put through various factory routine tests in order to

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eliminate any units that would be unsatisfactory for service. Tests included in this routine inspection vary among the manufacturers, but usually include a 60-cycle flashover of the unassembled bodies, and both 60-cycle and high frequency flashover of the assembled units, although sometimes the latter test is omitted. Porosity tests generally are made on samples selected from each firing batch of porcelain, and many companies run temperature change tests on samples of the assembled units from time to time. Some manufacturers include a mechanical test on their suspension insulators at a certain percentage of their rated strength as a regular routine test on all units. Routine factory tests usually follow the standards adopted by the A.I.E.E. and American Standards Association, which were developed for use as standard factory acceptance tests.

Although these factory routine tests are of great assistance to the manufacturers in keeping their products uniform, and the acceptance tests important to the purchaser, it is questionable whether, taken alone, they give complete indication of the life that may be expected of the insulators. It is believed, however, that supplementary tests can be performed that will give an indication of the life performance and relative merits of the various insulators under consideration. In confirmation of this, it has been the authors' experience that insulators that have performed best in the laboratory tests also have performed best in service.

Selection Test Followed by American Gas and Electric Company

Although the American Gas and Electric Company and its subsidiaries had conducted laboratory tests on insulators previously, they devised in 1922 a series of tests which were made on various makes of suspension insulators; these tests, with some changes and additions, have been repeated more or less periodically up to the present time. The object of these tests was specifically to determine, from the various makes of commercial insulators available in the United States, the insulator best adapted for transmission line service involving moderate loadings in an area where both high summer and low winter temperatures were encountered, keeping in mind that what it was hoped to obtain was an insulator that not only would show up well in the laboratory, but also would stand up over an extended period of time in service.

These tests were occasioned by the fact that a major construction program was being planned at that time for tying together various properties with 132-kv transmission lines. The mechanical test devised for the insulators consisted merely of subjecting them, while carrying normal line voltage, to the maximum loads for which these lines were being designed. This maximum design load, amounting to 6,000 lb, occurred on single suspension strings when the conductors were loaded with excessive ice. It was assumed that this condition might last for a period not exceeding 3 days. The 72-hr time-load test thus devised was followed by a further electrical test to detect any cracks that might have developed. This electrical test consisted of flashing over each unit individually by applying a damped-wave high-frequency voltage for 30 sec.

Some of the units passing the time load and electrical tests then were subjected to a thermal change test consisting of immersing the units first in boiling water for 10 minutes and then immediately transferring them to ice water for 10 minutes with a short high frequency test as previously described following the ice water immersion. Five complete cycles of this test were made. Porosity tests consisting of immersing broken porcelain samples of insulators in a water solution of eosin dye at a pressure of 260 lb per square inch for 14 hours completed the original test procedure.

In all subsequent tests on suspension insulators, there was included an ultimate electrical and mechanical test on all units passing the time-load, high frequency, and thermal change tests. In this test each insulator, while subjected to an electric potential of 60 kv, was pulled to destruction. Starting with a mechanical load of 6,000 lb, this was increased in 500-lb steps every 30 sec until electrical failure, at which time the electrical potential was

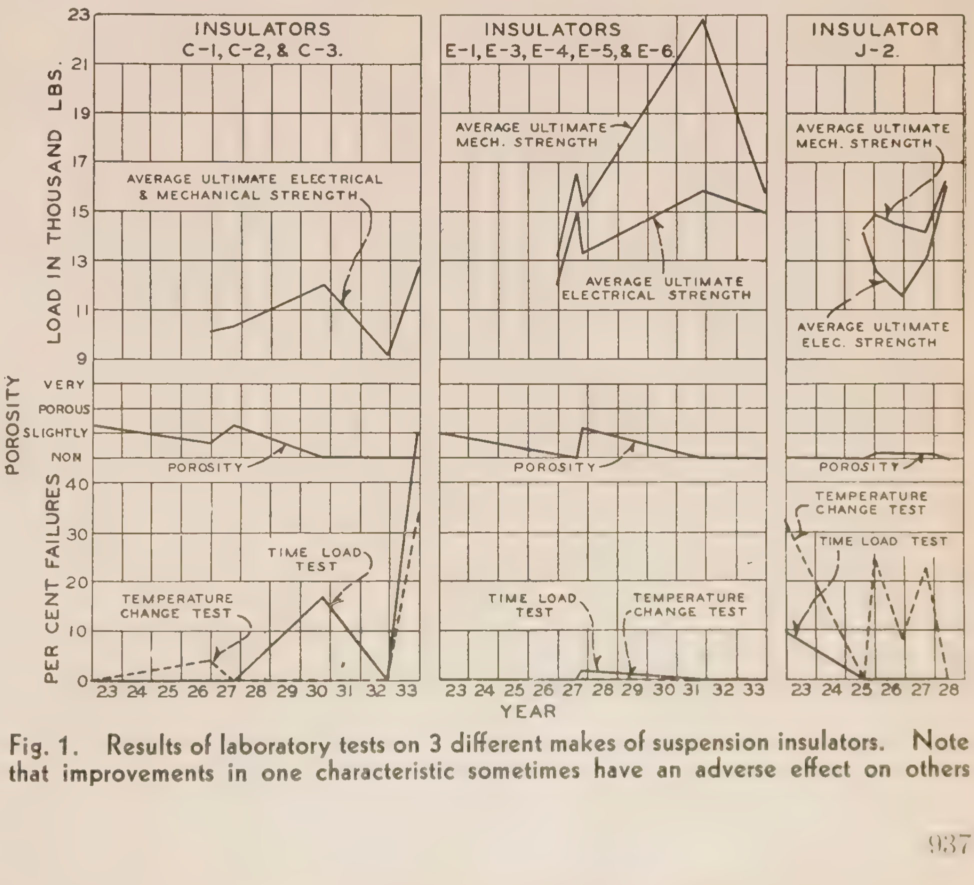

Fig. 1. Results of laboratory tests on 3 different makes of suspension insulators. Note that improvements in one characteristic sometimes have an adverse effect on others

TABLE I. LABORATORY TESTS ON SUSPENSION INSULATORS BY AMERICAN GAS AND ELECTRIC COMPANY

72 Hr. Time - Load Tests - % Failures

Insulator	Dec. 1922 Mechanical Failure	Dec. 1922 Electrical Failure	Aug. 1925 Mechanical Failure	Aug. 1925 Electrical Failure	Jan. 1926 Mechanical Failure	Jan. 1926 Electrical Failure	Dec. 1926 Mechanical Failure	Dec. 1926 Electrical Failure	Aug. 1927 Mechanical Failure	Aug. 1927 Electrical Failure	Oct. 1927 Mechanical Failure	Oct. 1927 Electrical Failure	June 1928 Mechanical Failure	June 1928 Electrical Failure	Oct. 1930 Mechanical Failure	Oct. 1930 Electrical Failure	Nov. 1931 Mechanical Failure	Nov. 1931 Electrical Failure	Feb. 1932 Mechanical Failure	Feb. 1932 Electrical Failure	Dec. 1932 Mechanical Failure	Dec. 1932 Electrical Failure	Dec. 1933 Mechanical Failure	Dec. 1933 Electrical Failure
A-1									100		0	17												
B-1							0	0	0	0														
C-1	0	0					0	0			0	0												
C-2															0	17								
C-3																					0	0	0	50
C-4																							0	83
C-5							0	0																
D-1	0	0					0	0																
D-2											0	0												
D-3	0	0																						
E-1	0	0																						
E-2	0	0																						
E-3							0	0			0	12												
E-4							0	0	0	0	0	0												
E-5											0	0												
E-6											0	0					0	0					0	0
E-7																	0	0						
E-8	10	40																						
E-9	0	0					0	0																
F-1							16	0																
F-2	0	0					17	0																
F-3																			0	0				
G-1	100	-							0	22														
G-2									0	17														
G-3									0	0	0	0												
H-1															0	8								
H-2																							0	0
I-1	0	0					27	0			0	0												
I-2	0	80																						
J-1			0+	0+																				
J-2	0	10	0+	0+	0	0	0	0			0	0	0+	0+										

Temperature Change Tests - % Failures

Insulator	Dec. 1922	Aug. 1925	Jan. 1926	Dec. 1926	Aug. 1927	Oct. 1927	June 1928	Oct. 1930	Nov. 1931	Feb. 1932	Dec. 1932	Dec. 1933
A-1					0	65						
B-1				9	[illegible]							
C-1	0			4		0						
C-2								0				
C-3											0	33
C-4												67
C-5				70								
D-1	0			4								
D-2						17						
D-3	100											
E-1	0											
E-2	0											
E-3				0		0						
E-4				0	0	0						
E-5						0						
E-6						0			0			0
E-7									0			
E-8	100											
E-9	100			0								
F-1				0								
F-2	0			12								
F-3										0		
G-1	67				0							
G-2					0							
G-3					0	0						
H-1								27				
H-2												17
I-1	0			0		0						
I-2	0											
J-1		0+										
J-2	33	0+	25	8		28	0+					

+ Tests conducted at manufacturer's plant. Electrical failures were on high frequency following time-load test.

removed and the test continued to mechanical failure. In addition, the thermal change test was revised to include a test on all units passing the time-load test and to consist of 10 cycles from boiling to freezing with high frequency flashovers following the fifth and tenth cycles only. In the more recent tests, half the units being put through the thermal change test have been subjected at the same time to a mechanical load of 3,000 lb, which is approximately the working load of the insulator. The procedure in the porosity test has been varied radically, the most recent test being at a pressure of 10,000 lb per square inch for 6 hours in an alcoholic solution of fuchsine dye.

During the period in which the tests have been conducted on the suspension insulators, checks also have been made at certain intervals as to wet, dry, and impulse flashover of the units and their puncture values under oil. These tests, however, never have been considered a part of the standard test procedure.

Laboratory test results are shown in Tables I, II, and III, covering, respectively, the time-load and temperature change tests, the porosity test, and the ultimate electrical and mechanical strength tests. An examination of these tables shows that in general the product over the period of years covered by the tests has shown an improvement, but also indicates that of the various insulators tested only comparatively few have had what might be called a perfect record. A comparison of 3 makes of units is shown in Fig. 1, in which insulators of one manufacturer, where they are substantially the same or where they are simply revisions of older units, have been grouped together. A further examination of the curves will indicate the difficulties experienced by some manufacturers in raising the ultimate strengths of their insulators without adversely affecting the results of the temperature change and time-load tests.

Attention is called to the temperature change test conducted in January and December 1933, the results of which may be found in Table I. In the test conducted in January 1933, all units were tested under a mechanical load of 3,000 lb, no failure being noted. In the test of December 1933, somewhat different results were obtained. In this test part of the insulators were tested with no load, while the remainder were tested under the 3,000-lb mechanical load. In the tabulation below, the results of the tests on the unloaded insulators are compared with those on the loaded insulators.

Insulator	Loading, Pounds	Per Cent Failures
C-3	0	0
	3,000	100
C-4	0	50
	3,000	100
E-4	0	0
	3,000	0
H-2	0	0
	3,000	50

The purpose of conducting the temperature change tests on units under load was to duplicate as nearly as possible conditions that had arisen in the field causing failures of insulators, duplicates of which previously had passed the usual temperature change tests.

TABLE II. LABORATORY TESTS ON SUSPENSION INSULATORS

POROSITY TEST

Insulator	Dec. 1922 Percentage				Aug. 1925 Percentage				Jan. 1926 Percentage				Dec. 1926 Percentage			
	Non Porous	Slightly Porous	Porous	Very Porous	Non Porous	Slightly Porous	Porous	Very Porous	Non Porous	Slightly Porous	Porous	Very Porous	Non Porous	Slightly Porous	Porous	Very Porous
A-1																
B-1													35	65		
C-1		67	33										39	61		
C-2																
C-3																
C-4																
C-5													57	43		
D-1		100											88	12		
D-2																
D-3	33	67														
E-1		100														
E-2		100														
E-3													84	16		
E-4													78	22		
E-5																
E-6																
E-7																
E-8	33	34	33													
E-9	33	67											33	67		
F-1													90	10		
F-2		67	33										82	18		
F-3																
G-1	100															
G-2																
G-3																
H-1																
H-2																
I-1		100											83	17		
I-2		50	50													
J-1					100+											
J-2	100				100+				83	17			79	21		

Insulator	Aug. 1927 Percentage				Oct. 1927 Percentage				June 1928 Percentage				Oct. 1930 Percentage			
	Non Porous	Slightly Porous	Porous	Very Porous	Non Porous	Slightly Porous	Porous	Very Porous	Non Porous	Slightly Porous	Porous	Very Porous	Non Porous	Slightly Porous	Porous	Very Porous
A-1	50	50			33	63	4									
B-1	50	50														
C-1					10	67	6	17								
C-2													100			
C-3																
C-4																
C-5																
D-1																
D-2					56	44										
D-3																
E-1																
E-2																
E-3					12	88										
E-4	100				12	88										
E-5					11	78	11									
E-6					0	78	11	11								
E-7																
E-8																
E-9																
F-1																
F-2																
F-3																
G-1	50	50														
G-2	50	50														
G-3	50	50			10	67	6	17								
H-1													100			
H-2																
I-1					12	88										
I-2																
J-1																
J-2					84	16			100+							

Insulator	Nov. 1931 Percentage				Feb. 1932 Percentage				Dec. 1932 Percentage				Dec. 1933 Percentage			
	Non Porous	Slightly Porous	Porous	Very Porous	Non Porous	Slightly Porous	Porous	Very Porous	Non Porous	Slightly Porous	Porous	Very Porous	Non Porous	Slightly Porous	Porous	Very Porous
A-1																
B-1																
C-1																
C-2																
C-3									100				100			
C-4														100		
C-5																
D-1																
D-2																
D-3																
E-1																
E-2																
E-3																
E-4																
E-5																
E-6	100												100			
E-7	100															
E-8																
E-9																
F-1																
F-2																
F-3																
G-1																
G-2																
G-3																
H-1																
H-2													100			
I-1																
I-2																
J-1																
J-2																

+Tests conducted at manufacturer's plant. Nonporous = no penetration. Porous = penetration of 1/32 in. or more but less than 1/8 in. Very porous = penetrations of 1/8 in. or more.
Slightly porous = penetrations of less than 1/32 in.

Examination of the results obtained from the series of tests that have been conducted to date, and as summarized in Tables I, II, and III, indicates that it is not difficult to eliminate some of the insulators from serious consideration. For example, insulator *A*-1 with 100 per cent mechanical failures on the August 1927 test, and with 17 per cent failures on the electrical and 65 per cent failures on the temperature change tests conducted in October 1927, was thus eliminated. Conversely, the series of insulators *E*-3 to *E*-6, inclusive, all of which are of substantially the same design with certain minor modifications, shows an almost perfect record from 1926 right through to December 1933, with the exception of a small lapse in the October 1927 tests. It would be expected, therefore, that an insulator showing such test results would be given superior rating, and that such performance would be given considerable weight in the final selection. The tests thus had the definite advantage that they eliminated from serious consideration insulators whose design or manufacture was obviously not on a sound basis.

Field Testing of Insulators

The first systematic field test by the American Gas and Electric Company on suspension insulators on which a record was kept was conducted in 1922. This test was made on some of the lines of The Ohio Power Company with insulator test sticks improvised by their engineers. The test sticks used were of 2 types: one a condenser stick for testing with the line alive, and the other a spark gap stick for testing with the line dead. The condenser stick consisted of 2 condensers in series with an adjustable spark gap placed in multiple with one of the condensers; the spark stick tester consisted merely of a dry battery, spark coil, and adjustable gap.

Field tests were continued on suspension insulators following the 1922 test, utilizing standard commercial types of testers; but not until 1929 were accurate records of the results of these tests kept. At present, the individual companies lay out their own testing programs, using results from previous reports as a guide so that the lines having the greater number of insulator failures are tested more frequently. An effort is made, however, to test at least 10 per cent of the insulators on each line every year.

In general the field tests conducted on suspension insulators have shown

them to be performing in an excellent fashion. Of 367,963 suspension insulators tested to date only 2,664 have been found defective, or about 0.724 per cent. The summation of the tests of the different makes of insulators is as follows:

Make of Insulator	Total Tested	Total Failures	Per Cent Failures
C	11,608	60	0.516
I	63,681	2,040	3.205
E	97,848	31	0.032
F	188,618	300	0.159
J	6,208	233	3.755
Total	367,963	2,664	0.724

A résumé of the results of the field tests conducted to date is given in Table IV. It may be seen that the service record of some of the makes of units is exceptionally good while that on other makes show a much higher percentage of failures.

In but 4 instances have groups of insulators been tested for a second time. It might be expected that in such tests, successive tests would show an increasing number of failures per year; but in the repeat tests conducted to date this is not definitely shown, the results being anything but uniform. They are given in the following tabulation:

Insulator	Installed	First Test	Second Test
C-1	1922	After 9 yr 3,990 tested 1 bad.	After 10 yr 3,955 tested 0 bad.
E-3	1925	After 4 yr 16,052 tested 1 bad.	After 7 yr 2,370 tested 0 bad.
			After 8 yr 2,929 tested 3 bad.
F-4	1917	After 5 yr 46,472 tested 27 bad.	After 12 yr 46,472 tested 8 bad.
J-1	1922	After 9 yr 5,182 tested 66 bad.	After 10 yr 5,167 tested 54 bad.

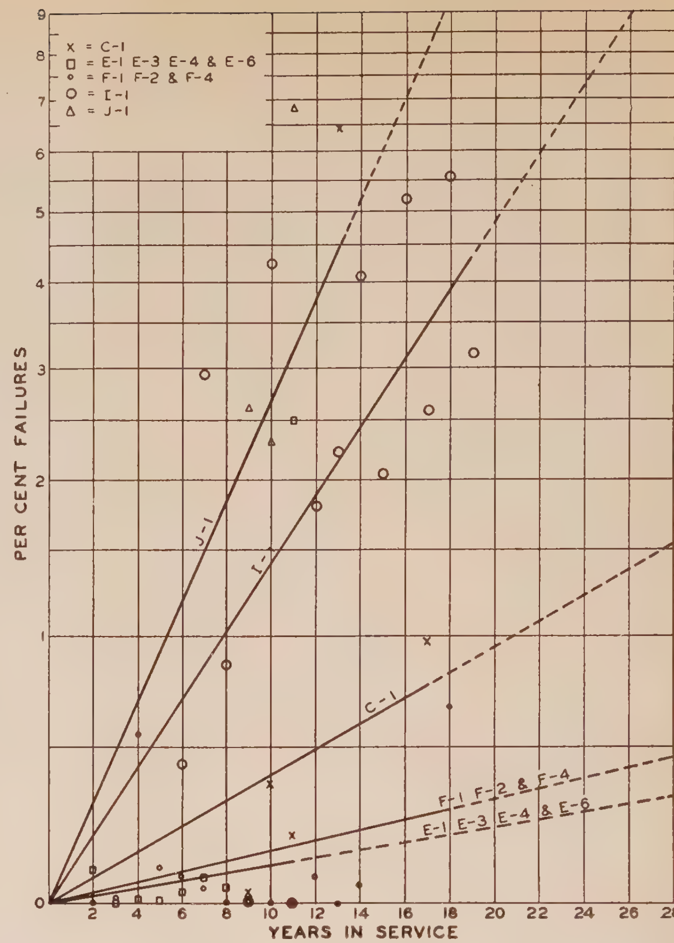

Fig. 2. Deterioration of insulators as revealed by field test data given in Table IV

TABLE III. LABORATORY TESTS ON SUSPENSION INSULATORS BY AMERICAN GAS AND ELECTRIC COMPANY

Ultimate Electrical and Mechanical Test – (Load in Thousands of Pounds)

Insulator	August, 1925						January, 1926					
	Electrical			Mechanical			Electrical			Mechanical		
	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.
A-1												
B-1												
C-1												
C-5												
D-1												
D-2												
E-3												
E-4												
E-5												
E-6												
E-9												
F-1												
F-2												
G-1												
G-2												
G-3												
I-1												
J-2	14.8	14.2	13.8	14.8	14.3	14.0	14.0	12.7	11.5	17.5	14.9	13.0

Insulator	December, 1926						August, 1927					
	Electrical			Mechanical			Electrical			Mechanical		
	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.
A-1							* 7.3	* 4.25	* 1.2	* 7.8	* 7.3	* 6.8
B-1	13.5	10.6	7.5	20.0	16.9	12.5	14.5	12.5	11.0	22.6	21.6	19.0
C-1	11.0	10.1	9.0	11.0	10.1	9.0						
C-5	11.5	8.3	6.0	20.0	20.0	19.0						
D-1	15.0	12.5	8.5	15.0	12.5	8.5						
D-2												
E-3	15.5	11.4	9.0	16.0	12.0	9.5						
E-4	15.5	13.4	10.0	19.0	15.8	13.5	16.4	15.0	13.7	19.6	16.6	14.3
E-5												
E-6												
E-9	16.5	13.9	6.5	16.5	14.5	10.0						
F-1	11.5	8.8	6.0	11.5	9.0	6.5						
F-2	12.0	8.9	6.0	12.0	8.9	6.0						
G-1							11.0	10.4	8.5	11.0	10.5	9.0
G-2							10.5	9.9	9.0	13.1	12.1	10.5
G-3							20.0	17.9	13.5	20.6	18.4	14.2
I-1	8.5	6.6	6.0	8.5	6.6	6.0						
J-2	15.0	11.6	10.0	16.0	14.5	12.0						

Insulator	October, 1927						June, 1928					
	Electrical			Mechanical			Electrical			Mechanical		
	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.
A-1	9.5	8.5	7.5	9.5	8.55	8.0						
B-1												
C-1	11.5	10.3	9.0	11.5	10.3	9.0						
C-5												
D-1												
D-2	18.0	15.2	13.5	18.0	15.2	13.5						
E-3	14.0	13.5	13.0	16.0	14.7	13.5						
E-4	16.5	13.3	11.5	17.0	15.2	13.5						
E-5	16.0	13.0	11.0	18.5	15.6	13.0						
E-6	17.0	13.6	8.0	17.5	15.0	13.5						
E-9												
F-1												
F-2												
G-1												
G-2												
G-3	12.5	11.1	9.5	15.5	13.0	10.5						
I-1	14.0	11.1	9.5	14.0	11.4	10.0						
J-2	16.0	13.1	6.0	16.0	14.2	12.0	18.5	16.1	10.5	18.5	16.3	12.5

TABLE III (Cont'd.)

Insulator	October, 1930						November, 1931					
	Electrical			Mechanical			Electrical			Mechanical		
	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.
C-2	12.8	12.0	11.0	12.8	12.0	11.0						
C-3												
C-4												
E-6							17.5	15.9	14.1	25.0	22.9	20.7
E-7							15.2	14.0	13.0	20.2	17.5	15.7
F-3												
H-1	23.1	22.1	20.3	23.1	22.1	20.3						
H-2												

Insulator	February, 1932						December, 1932					
	Electrical			Mechanical			Electrical			Mechanical		
	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.
C-2												
C-3							9.7	9.18	8.3	9.7	9.18	8.3
C-4												
E-6												
E-7												
F-3	13.8	12.9	10.8	13.8	12.9	10.8						
H-1												
H-2												

Insulator	December, 1933					
	Electrical			Mechanical		
	Max.	Avg.	Min.	Max.	Avg.	Min.
C-2						
C-3	13.1	12.7	12.3	13.1	12.7	12.3
C-4	9.1	9.1	9.1	19.2	19.2	19.2
E-6	18.2	15.0	12.1	18.2	15.8	14.2
E-7						
F-3						
H-1						
H-2	10.8	9.9	9.1	22.0	19.2	15.8

*Not previously tested at 6000 lb for 72 hr.

TABLE IV. FIELD TESTS ON SUSPENSION INSULATORS

Insulator	Date Installed	1929 Test No. Tested	1929 Test No. Failures	1929 Test % Failures	1931 Test No. Tested	1931 Test No. Failures	1931 Test % Failures	1932 Test No. Tested	1932 Test No. Failures	1932 Test % Failures	1933 Test No. Tested	1933 Test No. Failures	1933 Test % Failures	Total No. Tested	Total No. Failures	Total % Failures
C-1	1916										1431	14	0.98	1431	14	0.98
	1919							219	14	6.39				219	14	6.39
	1921				2890	25	0.87	2353	2	[illegible]				5243	27	0.52
	1922				3990	1	0.03	3955	0	0	725	4	0.55	4715	5	0.01 *
E-1	1920				240	6	2.5							240	6	2.5
E-3	1925	16052	1	0.006	7738	1	0.013	2778	6	0.216	3658	3	0.08	24927	11	0.036 *
	1926				150	0	0	510	0	0	1206	0	0	1866	0	0
	1927										203	6	2.95	203	6	2.95
	1930							480	0	0				480	0	0
E-4	1924				3274	0	0	3305	0	0				6579	0	0
	1925				52	0	0							52	0	0
	1926	956	0	0	13947	0	0	9542	0	0	1039	0	0	25484	0	0
	1929										19	0	0	19	0	0
	1931										382	0	0	382	0	0
E-6	1927							6070	3	0.05	219	0	0	6289	3	0.05
	1928							2824	1	0.035	13006	0	0	15830	1	0.006
	1929							840	0	0	924	1	0.108	1764	1	0.056
	1930							2172	3	0.14	3228	0	0	5400	3	0.055
F-1	1924							440	0	0				440	0	0
	1926	22937	2	0.009				100	0	0	3	0	0	23040	2	0.009
	1927										287	0	0	287	0	0
	1929										13	0	0	13	0	
F-2	1921							1091	0	0				1091	0	0
	1922							3175	0	0	830	0	0	3995	0	0
	1923							2729	0	0	378	0	0	3103	0	0
	1924				3280	0	0	5746	0	0	22285	1	0.005	30711	1	0.003
	1925				4018	8	0.20	861	0	0				4879	8	0.164
	1926	4000	0	0	4411	23	0.52	1842	0	0	10032	5	0.05	20285	28	0.14
	1927							351	0	0	4565	0	0	4916	0	0
	1928							2527	20	0.79	570	0	0	3097	20	0.65
	1929				264	0	0				1575	3	0.11	1839	3	0.16
	1930										2401	3	0.11	2401	3	0.11
	1931										56	0	0	56	0	0
F-4	1914							5754	137	2.38				5754	137	2.38
	1915							1845	5	0.27	22732	53	0.23	24577	58	0.24
	1917	46472	27	0.06	46472	8	0.017							46472	35	0.076 *
	1918							10157	5	0.05				10157	5	0.05
	1920										1323	0	0	1323	0	0
I-1	1914				439	17	3.86	4511	179	3.93	19043	616	3.23	23993	812	3.38
	1915				4851	254	5.62				9101	577	6.40	13952	831	5.96
	1916				2033	2	0.097	40	0	0	614	10	1.63	2647	12	0.46
	1917							130	15	11.54				130	15	11.54
	1918				1204	26	2.26	1910	78	4.08	2136	71	3.32	5250	175	3.33
	1919				103	1	0.97	46	2	4.35	60	1	1.68	209	4	1.92
	1920				75	0	0	60	0	0				135	0	0
	1921				118	5	4.25	60	0	0	279	7	2.51	457	12	2.63
	1922										2209	0	0	2209	0	0
	1923							847	0	0				847	0	0
	1924				3454	123	3.56	5639	47	0.83				9093	170	1.87
	1925				1376	6	0.04	751	0	0	75	2	2.67	2202	8	0.04
I-2	1914										430	0	0	430	0	0
	1915				30	0	0				250	0	0	280	0	0
	1916										105	0	0	105	0	0
	1918							657	0	0	214	0	0	871	0	0
	1920				45	0	0				190	0	0	235	0	0
	1921							55	0	0	120	0	0	175	0	0
	1925				348	0	0							348	0	0
	1927							74	0	0				74	0	0
J-1	1922				5182	66	1.29	5167	54	1.05	408	28	6.85	5590	148	2.65 *
	1923							618	85	13.75				618	85	13.75

*All or portion of insulators tested twice.

In order to compare the field performance of insulators with the results obtained in laboratory tests Table V has been prepared. All makes of insulators that were installed in the field during the same period in which they were tested in the laboratory have been included in this table. They have been rated according to the results of both laboratory and field tests. The importance of laboratory tests is attested by the fact that the ratings in the 2 columns correspond and are practically identical.

The graphical comparison of the results obtained in the field and laboratory tests on the type E insulators is shown in Fig. 3. Here again results indicate that insulators that test well in the laboratory also perform well in the field.

TABLE V. COMPARISON OF LABORATORY AND FIELD TESTS ON SUSPENSION INSULATORS

Insulator	Laboratory Tests: Date Tested	Time Load % Bad	Temp. Change % Bad	Porosity * %	Test Rating	Field Tests: Date Installed	No. Tested	% Bad	Test Rating
I-1	Dec. 1922	0	0	33	1	1922-23	3056	0	1
F-2	"	0	0	44	2	"	7098	.0	1
C-1	"	0	0	44	2	1922	8670	.075	3
J-1	"	10	33	0	4	1922-23	6208	3.75	4
E-3	Dec. 1926	0	0	5	1	1926	1866	0	1
E-4	"	0	0	7	2	"	25484	0	1
F-1	"	16	0	3	3	"	23040	.0087	3
F-2	"	17	12	6	4	"	20285	.138	4
E-6	Oct. 1927	0	0	44	1	1927	6289	.047	1
E-3	"	12	0	29	2	"	203	2.95	2

*Very porous is taken as 100%; porous, 67-2/3%; slightly porous, 33-1/3%; nonporous, 0%.

Deterioration of Insulators

The question of life expectancy of any piece of engineering equipment is one that should be raised every time that its design, manufacture, or purchase is considered, if the problem is to be handled on a rational and engineering basis. It is obvious, for example, that the rate of depreciation to be allowed on a piece of equipment depends on life expectancy, although frequently obsolescence plays the major part in that question. In the case of steel transmission towers, it is the general opinion among engineers that where no unusual climatic conditions exist that would accelerate rusting, the life of such a structure can be taken as a rather long period, possibly of the order of 50 years or more. The logical question is, therefore, if the structure and conductor are good for a 50-yr life, can the insulator be expected to last the same length of time?

It is apparent that the insulators on a given line taken by themselves may not have outlived their usefulness where the rate of deterioration is, say, in the order of only 10 per cent; yet when such a condition is reached the insulation of the line as a whole may have become totally unreliable. Thus, if the criterion of usefulness of a line is its ability to

carry power continuously except for such causes as are extraneous to the line itself, or, in other words, if a situation is reached where the majority of interruptions to the service are caused by insulator failures, then the end of the useful life of the insulation on that line has been substantially reached.

The percentage of failures of insulators determining the end of the usefulness of the insulation of a transmission line cannot be stated generally. It must be determined for each line individually according to the importance of uninterrupted service to that line. The limit possibly may have been reached when the total failures to date are between 5 and 15 per cent of the total insulators on the line.

To show what the experience of the American Gas and Electric Company has been along these lines, Fig. 2 has been prepared from the data on the field tests given in Table IV; years of service for the different insulators have been plotted against the summation of the percentages of insulator failures found to date. In these curves where a manufacturer has several different insulators that are substantially of the same design, they are grouped together. The curves as shown are necessarily approximate due to the scattered position of the points, but seem to indicate that a life expectancy of 50 years for suspension insulators is not beyond realization.

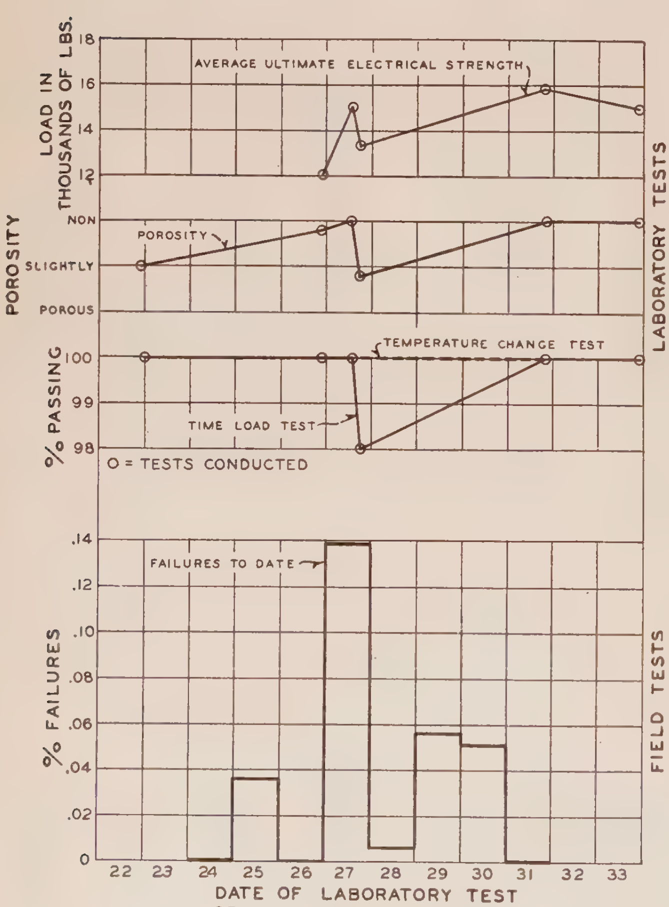

Fig. 3. Comparison of field and laboratory tests on type E insulators

Calibration of the Sphere Gap

A series of sparkover voltage calibration tests on sphere gaps using spheres of various sizes up to 200 cm in diameter are reported in this paper. Tests were made with gap spacings ordinarily used in practice, and with 60-cycle and both positive and negative impulse voltages. Since these tests as well as those of other investigators show that some of the A.I.E.E. standard sphere gap calibration curves are in error, it is recommended that those standards be revised. Recommendations are made for the adoption of separate calibration curves for positive and negative impulses and for correcting the 60-cycle calibration curves of large spheres.

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FROM THE TIME that electric potentials exceeding a few thousand volts have been in use, it has been standard practice to measure voltages with a spark gap. Needle point gaps were used extensively until 1913 or 1914. The disadvantages of using needles were chiefly that: (1) the points fused necessitating renewal after each sparkover; (2) sparkover voltages were inconsistent under a given condition; (3) the voltages were greatly affected by atmospheric conditions, particularly humidity, but also by temperature and barometric pressure; and (4) a needle gap has a large time-lag. Consequently, the use of the needle gap was limited to sustained low frequency measurements.

In the search for a more accurate measuring spark gap, it was found that the sphere gap offered several advantages over the needle gap. For example, it is not appreciably damaged when sparked over. It is relatively unaffected by humidity changes in the air, although it is affected by changes in air density; and, it appeared to have no time-lag or polarity effect, making it suitable for measuring both low frequency and high frequency voltages of both oscil-

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1. For all numbered references see bibliography at end of paper.

latory and impulse types of either positive or negative polarity. Unlike the needle gap, the sphere gap sparkover potentials are very consistent.

The use of the grounded sphere gap for measuring purposes was first proposed to the A.I.E.E. in 1913 by Chubb and Fortescue[1] and Peek.[2] Their tests were made on small sphere gaps not exceeding diameters of 25 cm (37.5-cm and 50-cm spheres were tested at relatively small spacings).

Peek's measurements of voltage were made chiefly with a voltmeter coil and a step-down transformer. Chubb and Fortescue rectified the capacitance current taken by an air capacitor and measured the average value of the rectified current with a d'Arsonval galvanometer. Based on his own measurements, Peek derived an empirical formula[2] for calculating the flashover voltages for spheres of different diameters and spacings. While no complete sparkover curves were taken on spheres larger than 25 cm in diameter, it naturally was assumed that the formula would apply for all sizes of spheres.

In 1914 the A.I.E.E. adopted calibration curves for sphere gaps having spheres 6.25, 12.5, 25, and 50 cm in diameter, respectively. The calibration of the 50-cm sphere gap did not cover the entire range from zero to diameter spacing. The highest calibration point was for 27.6-cm spacing. These adopted curves were based on the tests by Chubb and Fortescue and Peek. In 1928 the 50-cm sphere gap curve was extended and a 75-cm sphere gap calibration was added to the standards. It is believed that these additions were not based on actual test data. A calibration also was added for 2.0-cm sphere gaps.

When these original calibrations were incorporated in the A.I.E.E. Standards, sphere gaps were believed to be completely free from polarity and time-lag effects. The only known factors affecting the sparkover voltages were temperature and barometric pressure.

In the early stages of impulse testing the demand for extreme accuracy was not as great as it is today; consequently, sphere gaps were very acceptable standards. In fact, it would have been quite difficult to carry on the early impulse testing without the use of sphere gaps. However, with the advent of impulse generators producing potentials up to several million volts, even larger measuring spheres became necessary. These spheres of 100, 150, and 200 cm in diameter were not calibrated at that time on 60 cycles throughout their entire range. Calculated sparkover curves were used in the absence of test curves. Inasmuch as many small sphere gaps had been found to check the calculated curves with good accuracy, it was reasonable to have confidence in the calculated sparkover curves of the larger spheres.

Sphere Gap Inaccuracies

When the importance of standardized coördination of insulation became apparent, greater accuracy in voltage measurement was needed, and various investigators noticed inaccuracies in the sphere gap standard. It was found[3,4] that gaps with different sizes of spheres could not be checked accurately against each other, that there was a marked polarity effect[5,6] at certain spacings, and that when subjected to very steep impulse waves there was an appreciable impulse ratio.[7] It would seem that enough evidence has accumulated in the past few years to justify a general revision and extension of the A.I.E.E. sphere gap calibrations.

Method of Test—60 Cycles

For the 60-cycle data presented in this paper, a testing transformer with a voltmeter coil was used. Sparkover curves were taken on spheres 6.25, 12.5, 25, 50, 75, 100, and 200 cm in diameter. All of the tests were made on sphere gaps having one sphere grounded. A crest voltmeter reading, using the voltmeter coil, gave the voltage measurement.

In order to determine the accuracy of this method of measurement, several tests were made. Using an identical testing transformer as a step-down transformer, the voltmeter coil readings of the 2 units were checked against each other under various conditions of loading and over the complete voltage range of the transformers. This test showed that the voltage from the voltmeter coil was a definite constant proportion of the high side voltage. The wave shape of the high side voltage was measured on a cathode ray oscillograph using a large sphere gap as a capacitance voltage divider. This was found to be in close agreement with the wave shape of the voltmeter coil voltage.

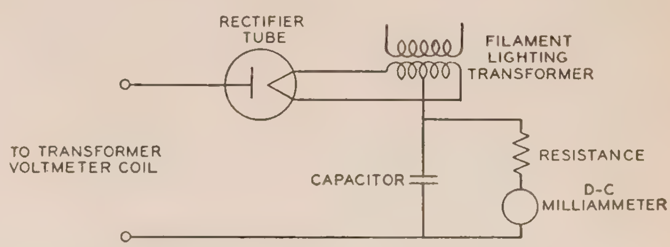


Fig. 1 (above). Schematic diagram of crest voltmeter

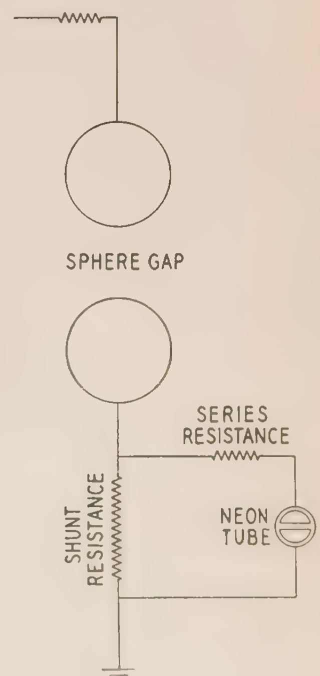


Fig. 2 (right). Neon tube polarity indicator used on 60-cycle tests

The crest voltmeter connected to the voltmeter coil consisted of a rectifier tube, a capacitor, a high resistance, and a d-c milliammeter as shown schematically in Fig. 1. It was calibrated with a 60-cycle voltage of known wave form. The calibration curve was practically a straight line when plotted between milliamperes and crest volts. This crest voltmeter was found to have a high degree of accuracy and the voltage readings were very consistent.

A resistance of 600,000 ohms was used in series with the sphere gaps on all 60-cycle tests. This resistance was placed as close to the sphere gap as possible without introducing the resistors into the field of the gap. Errors are likely to result if the line from the resistors to the sphere gap is too long. Corona on the line wire requires an appreciable amount of corona current to flow through the resistance. Under such conditions the voltage drop between the transformer and the sphere gap becomes excessive. The voltage drop due to the charging current to the spheres is negligible for all practical conditions.

All of the sphere gaps tested except the 75- and 200-cm spheres were mounted vertically in wooden frames that conform to A.I.E.E. specifications. In the 75- and 200- cm sizes the line potential sphere was suspended from the ceiling. The height of the grounded sphere above the floor was maintained at from 3 to 5 diameters. The clearances to nearby line and ground potential surfaces recommended by the A.I.E.E. were used.

At the same time that the 60-cycle sparkover curves were taken, determinations of the polarity of the voltage wave at the time of sparkover were made. This was done by placing a neon tube in the circuit of the grounded sphere as shown in Fig. 2. At the instant of sparkover, the capacitance of the transformer discharges and an impulse is impressed across the neon tube. This impulse is of the same polarity as the voltage wave at the time of sparkover. The polarity of the impulse is indicated by a glow surrounding one of the electrodes in the neon tube. The neon tube circuit must be well shielded from stray fields as it is very sensitive.

Table I—Sample Data Sheet for 60-Cycle Sparkover Test on 50-Cm Sphere Gap; Spacing, 11.0 Cm

Milliammeter Readings and Polarity of Sparkover	
0.295 neg.	0.292 neg.
0.292 neg.	0.292 neg.
0.290 neg.	0.285 pos.
0.293 neg.	0.288 pos.
0.292 pos.	0.290 neg.
0.290 neg.	0.285 neg.
0.292 neg.	0.292 neg.
0.288 pos.	0.290 neg.
0.282 neg.	0.292 pos.
0.292 neg.	0.288 neg.

Average milliamperes—0.290
5 positive polarity sparkovers
15 negative polarity sparkovers

Table II—Sample Summary Sheet for 60-Cycle Sparkover Test on 50-Cm Sphere Gap

Sphere Gap Spacing in Centimeters	Avg Crest Voltmeter Reading: Milliamperes	Avg Crest Voltmeter Reading: Crest Volts	Transformer Ratio	Transformer Kv Crest	Air Density Correction	Corrected Kv, Crest	% Positive Polarity Sparkovers
11.0	0.290	275	1000 : 1	275	0.998	276	25

Test Results—60 Cycles

Test points for 60 cycles were determined by taking from 10 to 20 consecutive sparkovers at each gap spacing. On each sparkover a crest voltmeter reading and a polarity indication were recorded. Table I shows a sample data sheet with the original data in the form in which it was taken. The milliammeter readings then were averaged and the voltage value determined as shown in Table II. The sparkover voltages for all sphere gaps tested are plotted on Figs. 3 to 9, inclusive. The voltages plotted are the averages of from 1 to 5 separate tests.

In order to study these test sparkover curves, a calculated curve is included on each figure for comparison. These curves are calculated using the Peek formula. The reason for including these calculated curves is that they furnish a common basis for reference. There are slight variations between the calculated curves and the A.I.E.E. curves, and furthermore there are no A.I.E.E. curves for the 100-cm and 200-cm spheres that could be used for comparison.

The family of curves shown on Fig. 10 was plotted to compare the test data with the calculated curves. The percentage error based on the test results is plotted against the percentage of diameter spacing of the spheres. It may be noted that these curves have a general similarity of shape. The dotted portion of the curve for 200-cm spheres is extrapolated. It is believed that this limited amount of extrapolation is accurate to within 1 or 2 per cent. Using this dotted percentage error curve and the calculated curve, the test calibration of the 200-cm spheres can be extended to 25 per cent of diameter spacing. This portion of the curve is shown dotted on Fig. 9.

The reason for the necessity of extrapolating the calibration curve is that the testing transformer used is limited in voltage to 800 kv crest. When 2 transformers are connected in series, the voltmeter coil of the grounded unit does not give an accurate reproduction of the high side voltage either in wave shape or voltage magnitude. However, the 2 transformers in series can be used to determine the polarity characteristics of the sphere gaps at voltages above 800 kv crest.

Variation of the polarity of the voltage wave at the time of sparkover with spacing has been termed the polarity characteristic. The polarity characteristic for each size of sphere gap is plotted with the test data on Figs. 3 to 9, inclusive. From these curves it can be seen that practically all of the sphere gap sparkover voltages are affected by polarity. In the range of spacings where both positive and

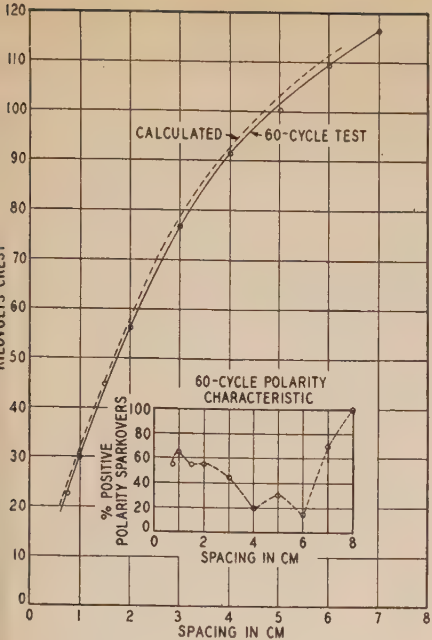


Fig. 3. 6.25-cm spheres

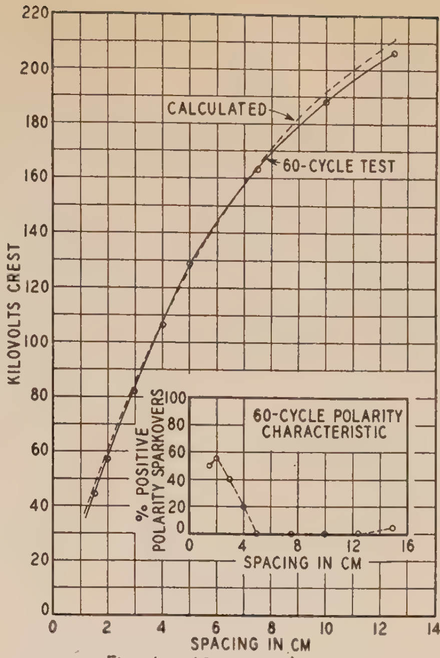


Fig. 4. 12.5-cm spheres

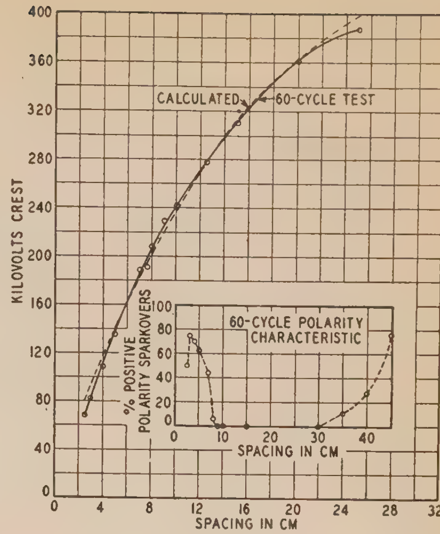


Fig. 5. 25-cm spheres

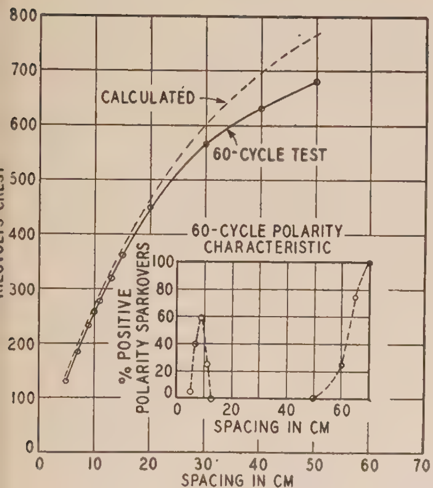


Fig. 6. 50-cm spheres

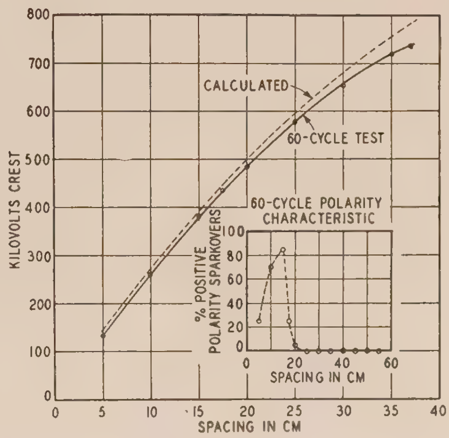


Fig. 7. 75-cm spheres

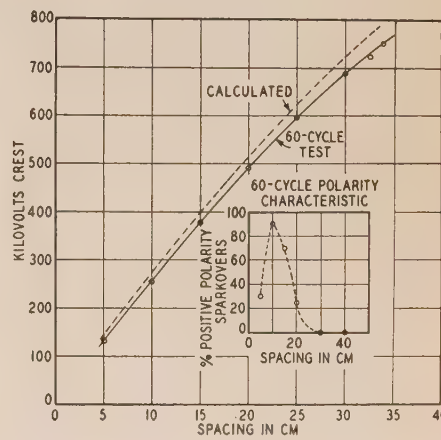
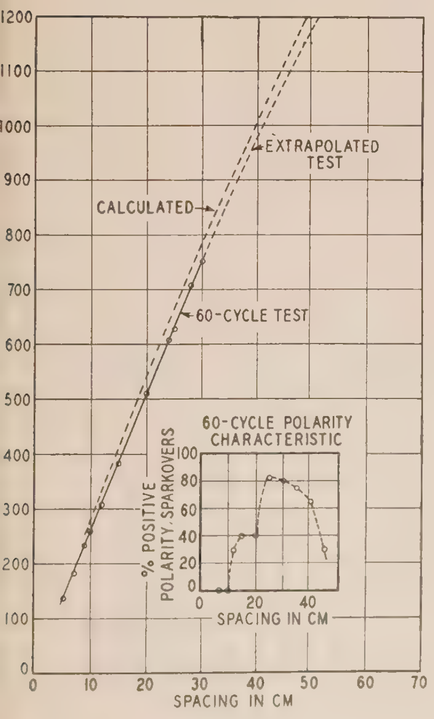


Fig. 8. 100-cm spheres

Figs. 3 to 9. Results of 60-cycle tests on sphere gaps, using various sizes of spheres; one sphere grounded in all cases

Fig. 9 (left). 200-cm spheres



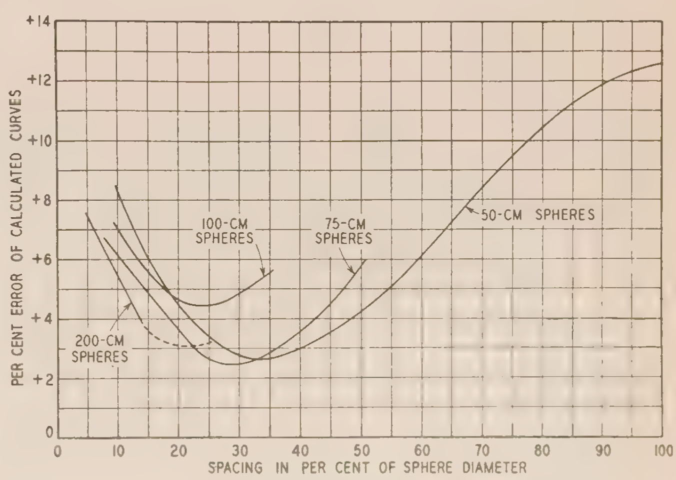


Fig. 10. Percentage error of calculated sphere gap curves based on 60-cycle tests

Plus error indicates that calculated curves are too high

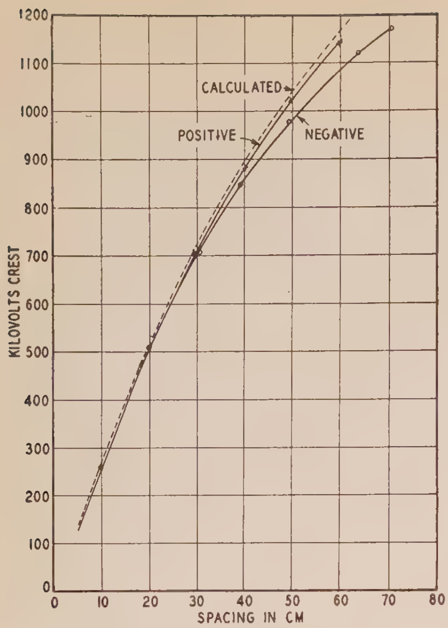


Fig. 11. 100-cm spheres

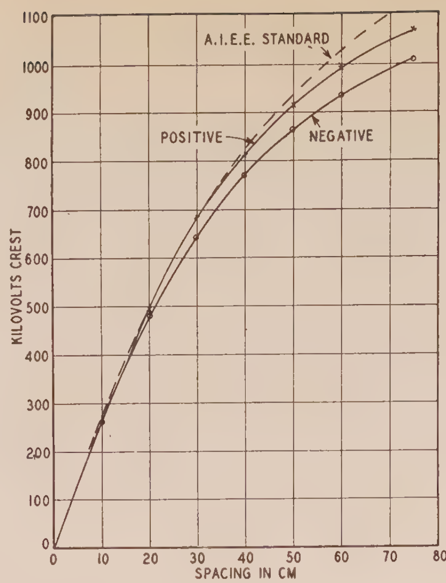


Fig. 12. 75-cm spheres

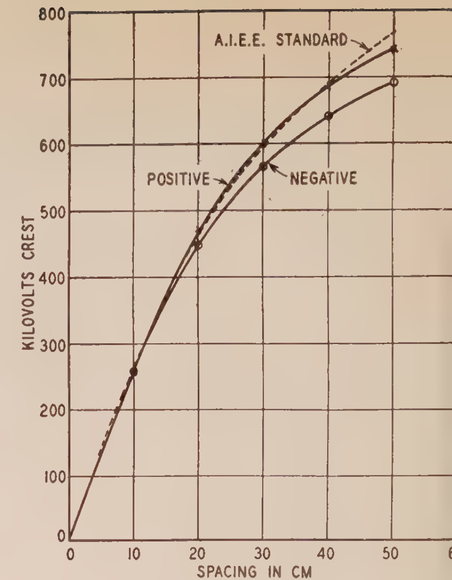


Fig. 13. 50-cm spheres

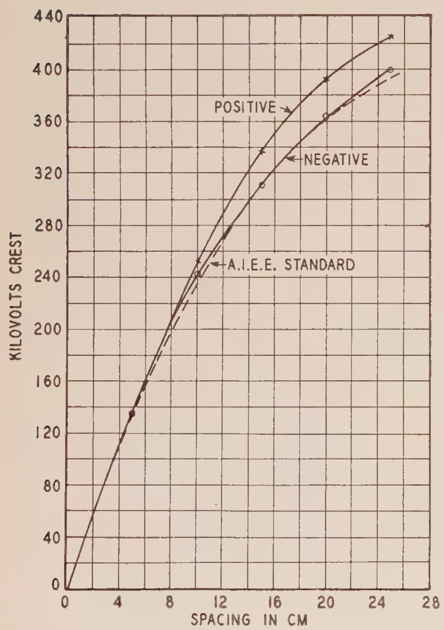


Fig. 14 (left). 25-cm spheres

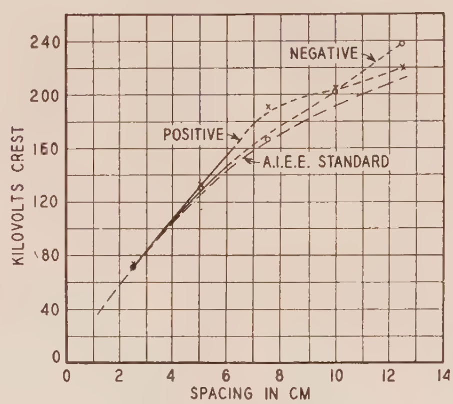


Fig. 15. 12.5-cm spheres

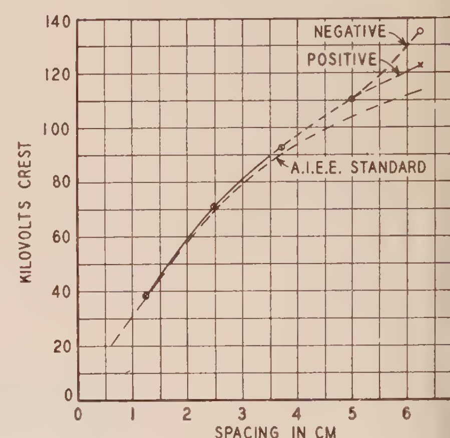


Fig. 16. 6.25-cm spheres

Figs. 11 to 16. Results of impulse tests on sphere gaps, using spheres of various sizes; one sphere grounded in all cases

negative sparkovers occur, the 60-cycle curve can be used for both polarities when measuring direct current or impulse voltages. However, in the range of spacings where the sparkovers occur consistently on one polarity, the 60-cycle curve can be used only for voltage measurement on that polarity.

Impulse Voltage Sparkover Curves

In order to use sphere gaps for measurement of impulse voltages, it becomes necessary to calibrate them on both polarities. In order to do this, (1) a source of voltage where the polarity can be controlled is essential, and (2) the measuring instrument must be free of polarity effect. The first requirement is satisfied by using full wave impulse voltages. The second requirement is satisfied by using 200-cm spheres in the range where both positive and negative sparkovers occur on 60 cycles, that is with from 10- to 50-cm spacing.

Accordingly, the 200-cm spheres were used as the reference in obtaining the sparkover curves for the 100-cm and 75-cm spheres on the 1.5×40-μsec full wave, both positive and negative polarity. The 60-cycle test curve of the 200-cm sphere gap was used as the standard. The voltage was limited to the sparkover of the 200-cm spheres spaced 50 cm since beyond this spacing the spheres probably show polarity effect. The sparkover curves were made by adjusting the impulse generator voltage and the sphere gap spacings until each sphere gap sparked over part of the time. In other words, equivalent spacings were obtained. The sparkover voltages of the 100- and 75-cm spheres are plotted on Figs. 11 and 12. Using the former of these 2 test curves the 100-cm spheres were used to calibrate the 50-cm spheres and so on down to and including the 6.25-cm spheres. Impulse sparkover voltages for the 50-, 25-, 12.5-, and 6.25-cm spheres are plotted on Figs. 13 to 16, inclusive. An A.I.E.E. calibration is included on each figure for comparison except fo

ables III to IX—Recommended Values for Sphere Gap Sparkover Calibrations for 60-Cycle Voltages and for Impulse Voltages of Both Positive and Negative Polarity. One Sphere Grounded in all Cases; All Voltages Are Crest Values

Table III—200-Cm Spheres

Spacing in Cm	Calculated Values, Kv (Peek)	Recommended Calibration, Kv: 60 Cycle and Negative Impulse	Recommended Calibration, Kv: Positive Impulse
10	278	259.5	259.5
20	540	509	509
30	781	755	755
40	1,009	979	979
50	1,220	1,181	1,181
60	1,417	*1,350*	*1,360*
80	1,752	*1,640*	*1,660*
100	2,038	*1,870*	*1,900*
120	2,280	*2,050*	*2,085*
140	2,485	*2,200*	*2,250*
160	2,655	*2,330*	*2,400*
180	2,800	*2,440*	*2,520*
200	2,915	*2,520*	*2,620*

alues in *italic* type are extrapolated.

Table IV—100-Cm Spheres

Spacing in Cm	Calculated Values, Kv (Peek)	Recommended Calibration, Kv: 60 Cycle and Negative Impulse	Recommended Calibration, Kv: Positive Impulse
10	275	259	259
20	516	505	505
30	721	703	710
40	896	860	880
50	1,041	988	1,025
60	1,166	1,088	1,130
70	1,268	1,167	*1,210*
80	1,355	*1,235*	*1,280*
90	1,435	*1,295*	*1,340*
100	1,500	*1,335*	*1,390*

alues in *italic* type are extrapolated.

Table V—75-Cm Spheres

Spacing in Cm	A.I.E.E. Standard, Kv	Recommended Calibration, Kv: 60 Cycle and Negative Impulse	Recommended Calibration, Kv: Positive Impulse
7.5	208.5	200	200
15	390	378	378
22.5	546	525	546
30	680	644	685
37.5	790	743	785
45	884	822	867
52.5	962	884	937
60	1,028	935	992
67.5	1,087	978	1,035
75	1,133	1,010	1,070

he 100-cm spheres for which none is available. The alculated curve based on the Peek formula is used or comparison for this size of sphere.

Comparison of 60-Cycle and Impulse Sparkover Curves

The 60-cycle polarity indicator shows that in eneral from very small spacings to approximately 5 per cent of diameter spacing, the positive and egative polarity sparkover curves should be practically the same. From approximately 25 per cent f diameter spacing to a spacing of one diameter it

Table VI—50-Cm Spheres

Spacing in Cm	A.I.E.E. Standard, Kv	Recommended Calibration, Kv: 60 Cycle and Negative Impulse	Recommended Calibration, Kv: Positive Impulse
5	137.8	130	130
10	262.5	259	259
15	372	362	372
20	460	448	472
25	533	515	544
30	594	566	600
35	646	604	648
40	694	635	688
45		660	718
50		685	743

Table VII—25-Cm Spheres

Spacing in Cm	A.I.E.E. Standard, Kv	Recommended Calibration, Kv: 60 Cycle and Negative Impulse	Recommended Calibration, Kv: Positive Impulse
2.5	73	72	72
5	133.8	136	136
7.5	187.3	194	196
10	234	242	252
12.5	275.5	279	300
15	310.5	310.5	338
17.5	340	339	369
20	361	363	394
22.5	380	378	412
25	394	390	426

Table VIII—12.5-Cm Spheres

Spacing in Cm	A.I.E.E. Standard, Kv	Recommended Calibration, Kv.: 60 Cycle and Negative Impulse	Recommended Calibration, Kv.: Positive Impulse
1.25	38.05	38.0	38.0
2.50	70.1	71.0	71.0
3.75	100.0	102.0	102.0
5.00	125.8	128.0	132.5
6.25	147.0	148.0	161.0
		60 Cycle Only	
7.50	164.3	163.5	
8.75	178.7	176.5	
10.00	191.0	188.0	
11.25	201.5	197.5	
12.50	211.5	206.0	

Table IX—6.25-Cm Spheres

Spacing in Cm	A.I.E.E. Standard, Kv	Recommended Calibration, Kv: 60 Cycle and Negative Impulse	Recommended Calibration, Kv: Positive Impulse
0.625	20.8	19.0	19.0
1.250	38.5	37.5	37.5
1.875	54.6	54.0	54.0
2.500	69.75	68.5	68.5
3.125	81.6	80.0	80.0
		60 Cycle Only	
3.750	90.3	88.5	
4.375	97.5	95.5	
5.000	103.5	101.0	
5.625	109.1	106.2	
6.250	113.3	111.0	

indicates that the negative polarity sparkover curve should be lower than the positive. Accordingly, for full wave impulse testing the negative impulse sparkover voltages should be in good agreement with the 60-cycle sparkover voltages throughout the range of spacings normally used.

An inspection of the test data shows that the negative and positive polarity impulse sparkover voltages are essentially the same at the lower spacings for all of the sphere gaps. Also, the negative polarity sparkover voltages are in good agreement with the 60-cycle sparkover voltages throughout most of the tested range of spacings except for the 6.25- and 12.5-cm spheres. In comparing the 60-cycle and impulse sparkover curves, it is believed that variations of 2 to 3 per cent are within the limits of accuracy for this type of measurement.

The 6.25- and 12.5-cm spheres have a higher sparkover voltage at large spacings on the 1.5×40-μsec full wave, negative polarity, than on 60 cycles. This condition is an indication of time-lag. Oscillograms of full wave impulse sparkovers show that these small sphere gaps do have appreciable time-lag at spacings greater than half of one diameter. Furthermore, as the spacing nears one sphere diameter, a very erratic zone of sparkover voltages is encountered. This is illustrated by the peculiar curvature of the impulse calibration curves on Figs. 15 and 16 just below a spacing of one diameter. The upper parts of these calibration curves have been drawn very freely through the test points. Since it was felt that these portions of the curves should not be used for voltage measurement they were not studied in detail. Parts of the curves that are believed to be unreliable for voltage measurement are shown dotted.

All of the sphere gaps tested show slight evidences of time-lag at a spacing of one diameter. It is believed that for very accurate measurements the impulse calibration curves should not be used beyond 80 per cent of diameter spacing. The 6.25- and 12.5-cm spheres should not be used beyond half of diameter spacing for impulse measurements. Measurements at 60 cycles, of course, are not affected by these limitations.

Effect of Polarity

Perhaps the greatest limitation of the present standard sphere gap calibrations is that they do not take into account the effect of polarity on the sparkover voltage of the spheres. The polarity effect is due to the unsymmetrical field between the spheres. The large ground surface near the grounded sphere is the upsetting factor. At spacings below 25 per cent of sphere diameter the polarity effect is negligible. Grounded and isolated sphere gaps have the same sparkover curve in this range.

Recent tests on shielded sphere gaps indicate that the effect of polarity can be eliminated with properly placed shields. The sparkover curve of the shielded sphere gap having one sphere grounded appears to agree very well with the sparkover curve for isolated spheres. The use of shields is not practical, however, in most laboratories due to space limitations.

Suggested Revision of A.I.E.E. Standards

A comparison of the test data presented in this paper with the present sphere gap calibration curves in general use suggests the following conclusions:

1. The sphere gap calibrations that originally were made on 60 cycles are fairly accurate for 60-cycle and negative polarity impulse measurements. The average error is of the order of 2 per cent.

2. Sphere gap standard curves that were not based on test data are inaccurate for 60-cycle, negative polarity impulse, and positive polarity impulse measurements throughout most of their calibrated range of spacings. These errors in some cases are as high as 15 per cent.

3. In general, all of the standard sphere gap calibrations are inaccurate for impulse measurements on positive polarity at large spacings.

Since these tests and those of other investigators have shown that some of the A.I.E.E. standard sphere gap calibration curves are in error, it seems evident that the standards should be changed. High voltage testing laboratories that use different sizes of spheres have been unable to agree on sparkover voltages. Using the proposed calibrations given in this paper, different sizes of spheres give the same voltage indication in the overlapping range.

The test data given in this paper have been taken under normal conditions of use of the spheres. No attempt has been made to influence the sparkover voltage by light radiations upon the sparking surfaces. The spheres were kept as clean as possible although excessive polishing was found to be unnecessary.

Recommended values for sphere gap calibrations on impulses of positive and negative polarities and 60-cycles are given in Tables III to IX, inclusive. These values are taken from smooth curves drawn from the data presented in this paper. For accurate impulse measurements, sphere gaps of 25-cm diameter and larger should not be used beyond a spacing of 80 per cent of diameter. Spheres smaller than 25 cm in diameter should be limited in spacing to half of the sphere diameter for all impulse measurements. The values given in *italic* type in the tables represent extrapolations not discussed in this paper, but it is believed that they can be used with confidence as being more accurate than the calculated sparkover voltages now in general use. It is recognized that some of the values given indicate an accuracy beyond that which should be used considering the experimental error.

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Some New Developments in Supervisory Control

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New developments in the direct selection system of supervisory control are described in this paper which also touches upon the systems and use of codes and gives examples of the use and operation of equipment.

THE PAPER in the February 1933 issue of ELECTRICAL ENGINEERING (p. 81–4) on the direct selection system of supervisory control explained the general theory of selection by utilizing a code of polarities. The history of the 2 previous selection systems was given and is here briefly abstracted.

The first or code system, introduced in 1921, operated to take the remote ends of the line conductors and switch them from unit to unit until the desired one was reached. The remote equipment selected then sent the same series of impulses back to the office and switched the near end of the line wires from control switch to control switch until the corresponding one was reached. The unit selected could then be operated at will.

The second or synchronous system, brought out in 1924, shifted both ends of the line wires simultaneously from point to point until the unit to be operated was reached. The unit could then be controlled as desired. This saved considerable time.

The direct selection system (1932) utilized no counting or stepping equipment, but by means of relays responsive to direct acting polarity codes the proper unit only at the remote location could be instantly selected and no other. A similar procedure gave the check back to the initiating station. Thus the change was from sequential operation of relays to direct operation and no time was lost in connecting the line wires to units on which no operation was desired.

This general idea has been kept, but important changes have been made since 1932 that are described in the following text, the object of which is to introduce the latest developments in supervisory control and to discuss the new selection and operating circuits. The progress has been chiefly with the 2-wire systems and, as a result, we are able to accomplish practically every type of operation at such split-second speed that now there are rarely advantages in the use of more than 2 wires, except for use as an emergency circuit.

Full text of a paper recommended for publication by the A.I.E.E. committee on automatic stations, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted March 20, 1934; released for publication May 2, 1934. *Not published in pamphlet form.*

Before proceeding further, a reminder in the form of explanations of a few of the terms connected with supervisory control may be desirable:

1. A *pulse* or *impulse* is the energizing of the line circuit for a short time and then deënergizing it, or the reverse of this cycle. Pulses vary in time interval and polarity in modern systems.

2. *Points* are units of operation. They may vary in equipment, but the usual point of control and supervision includes the control keys, pushbuttons, red and green indicating lamps, and check and disagreëment lamps which permit the opening and closing operations to be performed, as on a circuit breaker, and at the same time supervise the circuit so the dispatcher knows the position of the circuit breaker at all times.

3. A *control key* or *twist key* is a 2-position switch which determines whether the circuit breaker will receive the close or trip pulse.

4. A *check lamp* informs the dispatcher that the selection he intended has actually been made, and no other.

5. The *disagreement lamp* blinks when the position of the twist key disagrees with the position of its corresponding circuit breaker. When a circuit breaker trips automatically, an alarm sounds and the disagreement lamp blinks. This immediately notifies the dispatcher and enables him to locate instantly the particular circuit breaker affected.

6. *Supervision* denotes a signalling arrangement whereby the dispatcher is constantly informed of the condition or position of the remote apparatus.

7. An *escutcheon* is a small shield or panel which has assembled on it all of the control keys, pushbuttons and indicating lamps associated with a point.

8. *Relay pulls* means that the relay coil is energized.

9. *Relay drops* means that the relay coil is deënergized.

10. *Telemetering* or *remote metering* is obtaining from a remote station a meter indication of any variable quantity.

In the 2-wire system previously described, pulsating direct current was utilized in some of the selections, but a simpler arrangement has been developed. The line circuit relay equipment is reduced to a pair of receiving relays responsive to the 2 d-c polarities, as shown in Fig. 1.

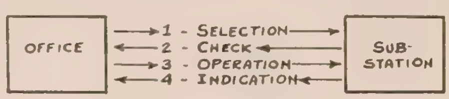

Fig. 1. Line circuits of simplified arrangement of 2-wire system

Codes Used in Operation

It will be recalled that an operation may be divided into 4 distinct steps, namely, selection, check, operation, and indication. When an operator initiates an operation, a selective impulse is sent from the office and received at the substation. The latter immediately sends a verifying impulse back to the office. After the operator has been assured by the verifying impulse that his selection is right

he proceeds to operate the remotely located device. When the remote operation is complete, indication of the change is sent to and recorded on the office board. This is illustrated in Fig. 2.

The characteristics of these impulses may be governed by the polarity of impulse, length of time of impulse, length of time between impulses, number of impulses, or combinations of these. Taking, for instance, the selection of any one of a group of 5 remote units, some of the selecting codes with corresponding checks which might be used are suggested in Fig. 3. A different code is used for checking than for selecting with the exception of code 3. This is done to get the same over-all time for each code, which in this case is approximately $^1/_4$ sec. It will be noted that a short positive pulse is used for selection in code 1 and a long positive pulse is used for the check. Similarly, code 2 uses a long positive pulse for selection and a short positive pulse for the check. Code 3 uses a short positive pulse immediately followed by a short negative pulse for selection while the same combination is utilized for the check. Codes 4 and 5 are identical with codes 1 and 2 except that negative impulses are used instead of positive ones. The complete selection diagram with description is given in the appendix, for those interested in the details of the individual circuits.

Scheme *B* shown in Fig. 4 varies from scheme *A* of Fig. 3 in that it uses 1 and 2 pulses (all short) instead of a combination of short and long pulses. The over-all time of selection and check for scheme *B* is approximately $^1/_3$ sec since arrangements are used to hold long enough after the first pulse to determine if a second pulse is to follow. Timing relays are therefore used as in scheme *A*.

Scheme *C* shown in Fig. 5, uses a series of impulses, both positive and negative, with timing relays partially eliminated. Here again, the over-all time of selection and check is approximately $^1/_3$ sec. Some timing is required because it is necessary to distinguish between a positive pulse followed by a negative one with and without a pause.

Scheme *D* in Fig. 6 uses 3 pulses and has the check pulse immediately following the selection pulse, i. e., select-check-select-check-select-check. With such a scheme, it is possible to shorten the pauses between pulses, and no timing relays are required. The pauses are automatically taken care of by the time required for switching the relays from sending to receiving positions. The over-all timing of scheme *D* is approximately $^1/_2$ sec.

Summing up the advantages of these various schemes, it appears that since speed of operation, simplicity of circuit, number of relays required, etc., must be considered, scheme *A* would be preferred on a small layout of about 5 operations and scheme *D* with 3 or more pulses each way would have definite advantages in the larger stations. For a station where 100 operations are required, the timing for selection and check would be approximately 1 sec for any one of them using scheme *D*.

Fig. 2. The 4 steps of a supervisory control operation

When considering any form of supervisory control, it must not only take care of the control of 2-position devices such as circuit breakers, or the starting and stopping of machines, etc., but it must also permit the use of the various established auxiliaries such as telemetering, synchronizing, position control, supervision only, and telephony. It is also necessary to design the line circuit so that the lines may be drained of any induced voltages and still not interfere with operation. In the new supervisory control circuits, all of these features are incorporated. Definite advances have also been made in 2 of the auxiliary operations, remote synchronizing and remote position control, which formerly required 2 points, but now use only one.

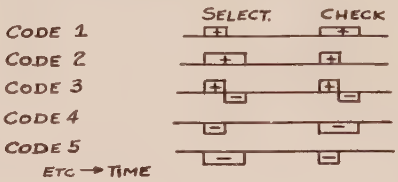

Fig. 3. Scheme A: Short and long pulses

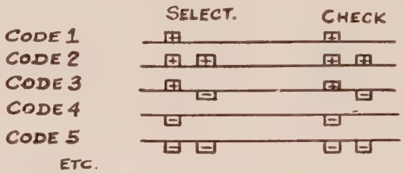

Fig. 4. Scheme B: One and 2 short pulses

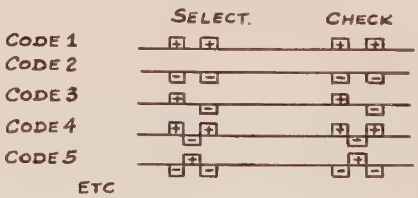

Fig. 5. Scheme C: Short pulses with and without pauses

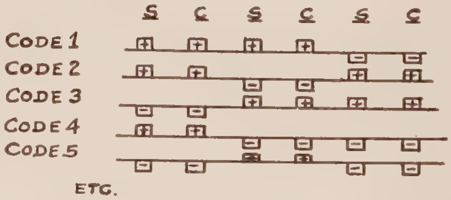

Fig. 6. Scheme D: Three pulses each way; each selection pulse followed with check pulse

Figs. 3 to 6. Four different combinations of impulses for accomplishing supervisory control operations

Examples of Remote Control

The new remote position control is of particular interest. With it, flexible operation is secured of remotely located transformer tap changers, voltage regulators, motor operated rheostats, gate openings, valve settings, or any other similar multi-position device. The changes of position are indicated to the

dispatcher as they take place, enabling him to stop at any desired point. Furthermore, once it is stopped it may be started and stopped at will in the same or opposite direction without reselection. For example, consider a hydroelectric generator running in a remote automatically controlled station. With the gate opening set at 0.8, it is desired to lower the generator output by closing the gates to 0.6. The gate mechanism has a rheostat connected as a potentiometer across the battery and is so arranged mechanically on the gate or governor mechanism that the moving arm of the rheostat varies its setting with the gate position. The switching is arranged so that the following operations take place:

1. The dispatcher operates the pushbutton (operation 1) to select this particular control function (gate position). With the lighting of the check lamp on the dispatcher's escutcheon showing him he has made the correct selection, the open circuit voltage of the station control battery appears on the meter. This meter has 2 scales, one registering the full scale of the battery voltage expressed in per cent and the other calibrated in gate opening from 0 to 1 in steps of tenths. Thus the dispatcher knows the actual voltage of the battery at the generating station and can use the percentage reading as a multiplier on his gate opening indication.

2. The dispatcher presses the check pushbutton (operation 2). This causes the meter reading to be transferred from the battery to the potentiometer and gives him the gate opening at that instant. He corrects this reading by the percentage multiplier he obtained when he first selected the point.

3. Since he wants to reduce the gate opening, he operates the twist key on his escutcheon to the "lower" position (operation 3) and presses the "master-operate" pushbutton (operation 4). This starts the governor synchronizer motor in the "decreased speed" direction and causes the gates to close. In a hydroelectric station there is usually some lag at this point which would not occur in the control of a tap changer, for instance. Here, the meter reading will not have reached the 0.6 opening due to the inherent lag in the governor and gate mechanism.

4. The dispatcher again presses the check pushbutton (operation 5) and the synchronizing motor on the governor stops but the meter reading remains. Thus he is able to observe the lagged action of the gate position. If, when the meter stops, the travel is not enough, he repeats the action by again pressing the master control followed by the check pushbutton. If he overshoots his 0.6 position, he turns the twist key to the "raise" position and presses the master control. The synchronizing motor now runs in the opposite direction and starts the chain of events that causes the waterwheel gates to open. Pressing the check button again causes this action to stop. Thus he is able to set the gate opening accurately at the 0.6 point. After a little experience, it will not be necessary for the operator to use more than one trial to secure the desired gate opening.

5. The dispatcher releases the set by returning the selection pushbutton to the normal position (operation 6).

It may be seen that he not only has complete control in getting an accurate setting but he knows, by the meter reading, the continuous status of the apparatus.

An equipment has also been developed to meet the requirements of the small installation. This junior equipment has been standardized to a very definite layout. It is limited to the control of 5 units and to 1 station per pair of line conductors. By such a move, it is possible to have the substation equipment housed in a single small relay case which may be added to an existing control board in a similar manner to a protective relay. The dispatcher's equipment is housed in a small cabinet for desk mounting.

The 6 usual types of supervisory control functions are:

1. Combination of control and supervision.
2. Control only.
3. Supervision only.
4. Telemetering.
5. Synchronizing.
6. Position control (with telemetering).

Combination of any 5 of these may be used on the junior equipment.

To see how it may fit into actual service requirements, let us take a few examples. First, a single-unit automatically controlled hydroelectric station is an ideal application.

Point No. 1. Start and stop the generator. Supervision is taken from the generator breaker.

Point No. 2. Telemetering of head. The dispatcher is able here to get an accurate reading of the amount of water available and therefore of the amount of load he can take from the plant.

Point No. 3. Position control of the waterwheel gates. This has been previously described. He is able to adjust the output of the station to any desired amount.

Point No. 4. Supervision of the lockout relay. Since the protection of an unattended station is divided into 2 parts, trouble outside which merely takes the equipment temporarily out of service and trouble inside which operates the lockout relay, the dispatcher knows if it is necessary to send a maintenance man to investigate and repair.

Point No. 5. This is a point of control and supervision which may be used for an outgoing feeder, a station service feeder, or any other one operation.

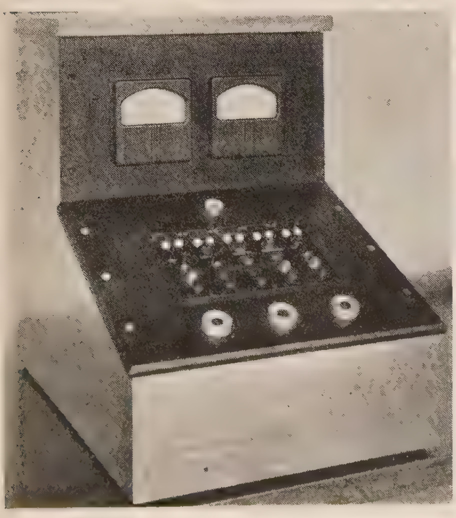

Fig. 7 (left). Dispatcher's cabinet arranged for desk mounting

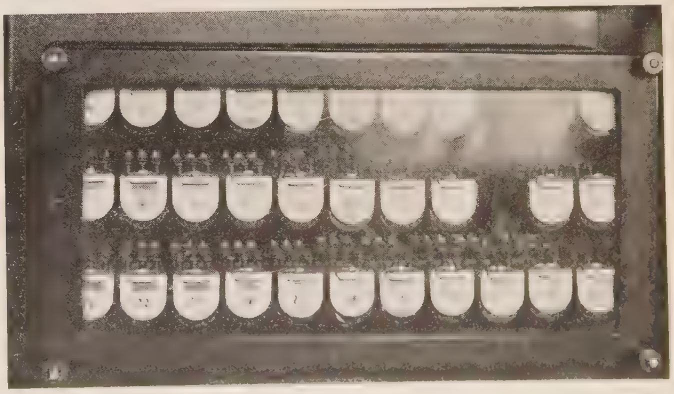

Fig. 8 (right). Substation equipment arranged in single relay case for mounting on substation panel

Second, in a single unit railway substation, the 5 points may be used in corresponding ways.

Point No. 1. Start and stop the rectifier, converter, or motor generator set. Supervision may be taken from the d-c line breaker showing when the unit goes on the line.

Point No. 2. Telemetering of load.

Point No. 3. Supervision of the lockout relay.

Points No. 4 and 5. Control and supervision of 2 outgoing d-c feeders.

Third, a small a-c distribution station with an incoming line and 3 low tension feeders could be equipped with this system.

Point No. 1. Control and supervision of the breaker on the incoming line.

Point No. 2. Telemetering of total load.

Points No. 3, 4, and 5. Control and supervision of the 3 low tension feeder breakers.

Similarly, the junior equipment is applicable to the remote control of pumping stations, industrial substations, ventilating fans, and other devices.

Summarizing, the progress in the last year and a half has been the simplification of selection and control circuits and the development of the junior all purpose standardized equipment. In all of this, proved standard relays with their high speed and reliability have been retained.

Appendix—A Simple Selection Circuit

With the set normally at rest, relays 6 and 9 (Fig. 9) at the office normally are energized or "up." The remaining relays are deënergized or "down." At the substation, relay 6 is up. The codes used are:

1. Short positive pulse.
2. Long positive pulse.
3. Short positive pulse, short negative pulse.
4. Short negative pulse.
5. Long negative pulse.

For the 5 points, we have:

Point	Selective Code	Check Code
1	1	2
2	2	1
3	3	3
4	4	5
5	5	4

Operator or dispatcher wishes to select the first point. He therefore depresses $K1$. In time sequence, the operation at both the office and remote substation ends of the line wires are as follows:

Office	Substation
1. $K1$ closed (to send code 1)	
2. Relay 7 pulls (through *b* contact of relay 3) (puts positive battery on line) (Relay 9 holds, being slow-releasing)	
3. Relay 1 pulls	Relay 1 pulls
(Relay 6 also holds)	(Relay 6 holds)
4. Relays 3 and 5 pull in series	Relays 3 and 5 pull
(Relay 3 locks in)	(Relay 3 locks in)
5. Relay 7 drops (Relay 9 locks in)	
6. Relay 1 drops	Relay 1 drops
(Relay 5 holds in, slow)	(Relay 5 holds)
(Relay 6 locks)	(Relay 6 locks)
7. Relay $B1$ pulls	Relay $F1$ pulls
(Relay $B1$ locks in)	(Relay $F1$ locks)
8. Relay 5 drops	Relay 5 drops
9. Relay 3 drops	Relay 3 drops

Thus when $K1$ is pressed, $B1$ at the office and $F1$ at the substation are energized.

The check back to the office is accomplished in exactly the same way, since the sending and receiving relay equipment is duplicated at each end. The proper selection is thus assured before any equipment in the remote station may be operated.

The operator then may set the twist key to the desired position (trip or close) and press the master control pushbutton. The trip or close code is sent to the substation in the same way previously described for the selection, which results in operating the remote unit. As the remote unit changes its position, a contact is made to send the supervision code to the office. Thus the lamps are changed on the dispatching board to correspond with the new position of the remote device.

When $K2$ is operated, relay 7 is not dropped when relay 3 pulls, because the circuit of $K2$ does not go through the *b* contact of relay 3, so relay 7 remains energized until relay 9 drops. Meanwhile, relay 6, which releases faster than relay 9, has dropped. As relay 7 drops, relay 1 is deënergized and $B2$ pulls since relay 6 is down. Then relay 5 drops, releasing relay 3. Relays 6 and 9 pull again and restore the circuit to its normal condition.

$K3$, when operated, functions the same as $K1$, except that relay 8 is pulled by relay 3. As soon as relay 7 drops, relay 8 puts the negative impulse on the line, pulling relays 2 and 4 at each end. Relay 4 opens the circuit of relay 8, which drops and stops the negative pulse. Relay 2 drops selecting relay $B3$. Relay 5 drops and releases relays 3 and 4.

Pushbuttons $K4$ and $K5$ operate like $K1$ and $K2$ except that relays 8, 2, and 4 pull instead of relays 7, 1, and 3. Thus, relays $B4$ and $B5$ are selected.

The junior equipment uses scheme A (Fig. 3) for the 4 steps of operation (selection, check, operation, supervision). On applications where the junior equipment cannot be applied, such as those requiring more than 5 points, scheme D (Fig. 6) usually is used.

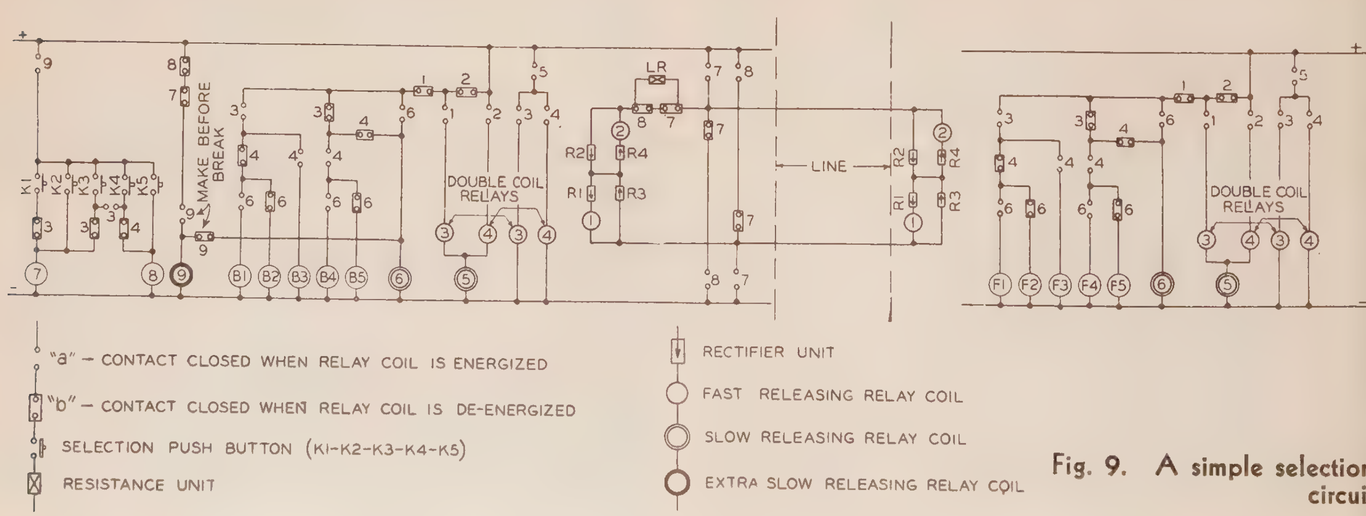

Fig. 9. A simple selection circuit

Selsyn Instruments for Position Systems

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Selsyn instruments are miniature salient pole synchronous machines excited by alternating current. They are used to transmit electrically, to one or several of the instruments acting as the receivers, the rotation given to another of the instruments acting as a transmitter. This paper presents a study of the behavior and accuracy of these instruments at standstill and under synchronous rotation giving results equally applicable to large Selsyn power motors and generators. The data presented are useful in connection with the problems of remote control, synchronous coupling of power drives, the transmission of indicating signals, or remote metering.

STRUCTURALLY a Selsyn device may have several variations of form but the instrument type, in particular, is simply a small salient pole synchronous machine. The transmitter-receiver system consists of one or more miniature synchronous motors (receivers) whose 3-phase armatures are connected to a second synchronous machine operating as a generator or transmitter. The transmitter may be of identical size or larger if several receivers are connected. The field windings are excited in parallel with alternating current, instead of direct current as for synchronous machines, to provide a synchronizing torque when both the receiver and the transmitter are at standstill. This characteristic distinguishes the Selsyn motor from the synchronous motor.

The manner in which the instruments are connected in a simple system consisting of one transmitter and one receiver is shown in Fig. 1. The secondary winding is a 3-phase winding generally connected in wye. The primary winding is usually a coil winding on salient poles. However, a uniform, smooth air gap may be used with the primary winding either a single-phase distributed winding or a 3-phase winding. Still other variations of form have been suggested and used but these are special instruments of no general interest.

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Paper submitted March 23, 1934; released for publication May 3, 1934. *Not published in pamphlet form.*

The 2 instruments of a Selsyn system as shown in Fig. 1 will maintain duplicate positions, when either one or the other is moved, due to an action which can be explained as follows. When the rotating members are in corresponding positions the voltage induced in the secondary winding of one instrument balances that induced in the secondary of the other. Therefore, no secondary current flows. If either instrument is turned out of the position of correspondence the sum of the voltages is no longer zero and a current flows in the secondary windings. This produces a torque causing the other instrument to turn and restore the balance of the voltages. Thus duplicate positions are maintained. Of course, if the secondary voltages of the 2 instruments are inherently not equal a secondary current will always flow. But when the instruments are in duplicate positions none of this secondary current is in the cross axis with respect to either rotor and, therefore, there is no torque. However, when one instrument is turned out of the duplicate position, a component of the secondary current creates a cross field in each instrument. A torque results which turns the instruments to duplicate positions.

Noteworthy applications of Selsyn instruments, in large numbers, have been for remote control purposes. In the field of theater lighting they have

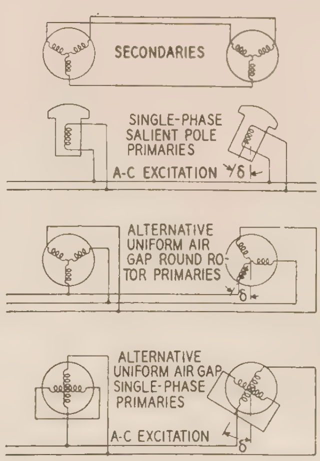


Fig. 1. Diagram of windings and connections for Selsyn system

made possible smooth variation of effects and simultaneous or independent operation of lighting units. Greater flexibility and easier control have been gained. The Chicago Civic Opera House is an outstanding example. On board ships they are used for signaling from the bridge to engine room

and for the control of searchlights and other apparatus. In the industry they are used to indicate or control the position of valves, etc., and for signaling between operating stations. In the power generation field they have been used for remote metering, measuring of water levels at different points, measuring of the contents of storage tanks, as remote tachometers, and for many miscellaneous purposes. For public works their noteworthy usefulness is for the control of lift bridges or drawbridges where the 2 ends or halves must be synchronized. As specific meters, indicators, or recorders their uses have been extensive.

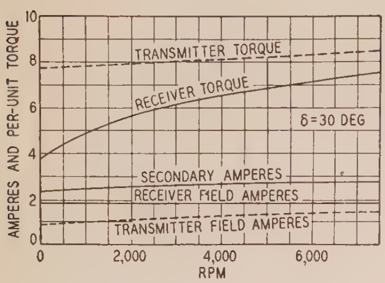


Fig. 2. Speed-torque curves of Selsyn instruments developing 0.3 hp at 7,000 rpm

Because the success of the instruments depends upon the accuracy of the receiver in duplicating the motion of the transmitter it is important that the torque-angle characteristic be known. Moreover in order to build highly accurate and sensitive devices it is necessary to know the influence of the different features of the construction. And, furthermore, the prospective user must be aware of any latent behavior such as oscillation or asynchronous torque. In the following analyses formulas are developed for the various forms of Selsyn instruments determining the standstill torque, current, and power input as a function of the displacement angle between the positions of the rotors. Then the speed term is introduced to derive formulas for the same functions under synchronous rotation. They are derived by the 2-reaction theory of Blondel[1] and are expressed in terms of coefficients for which expressions are given in Section III of this paper, covering the case of salient poles. The formulas for the round rotor case are given as derivatives in which the 2-reaction coefficients are equal.

Saturation is neglected without affecting the results appreciably. Where it must be taken into account judicious shading of the coefficients will allow the method to be used with good accuracy. Core loss is likewise neglected. Other assumptions are that the armature magnetomotive force is sinusoidally distributed in space and that the mutual inductance of the armature and field circuits is a first harmonic only with respect to the electrical space angle.

Results

The magnitude of the torque tending to maintain duplicate positions is, of course, most important. The strength of this torque when salient poles are used compared with that when the air gap is uniform is an important question. It is also valuable to know the strength of the torque when single-phase excitation is used compared to that when the primary windings are 3 phase. The foremost results are the expressions which make it possible to calculate accurately the torque under these various conditions. Space does not permit illustration of all the features of the performance of the instruments but several important conclusions and illustrations of the calculations may be made.

The synchronizing torque of the salient pole instrument exceeds that of the uniform air gap type* under normal conditions even when there is a short circuited winding in the quadrature axis. It is true that such a winding reduces the quadrature reactance and increases the torque as is indicated by eq 24 where, for practical purposes, $Z_q = x_q$. Actually, however, the leakage reactance and the resistance of the winding prevents as large an increase in torque as results when salient poles are used.

At standstill the synchronizing torque of the salient pole type exceeds that of uniform air gap instruments with 3-phase excitation. This is due in part to the addition of a reluctance torque which does not exist in the 3-phase case. This statement, of course, is subject to the details of the design but is true for ideal conditions with equal physical sizes.

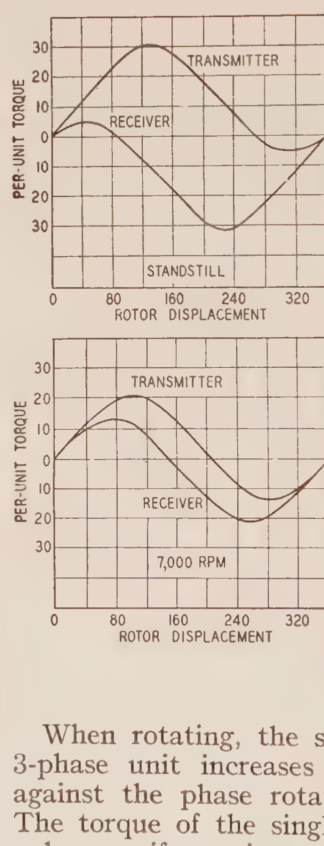


Fig. 3 (left, above and below). Torque-angle performance of Selsyn instruments designed for 0.3 hp at 7,000 rpm

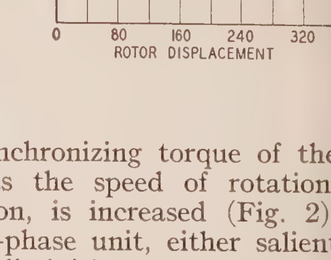


Fig. 4 (below). Power-angle performance showing watts returned to the line by receiver with 3-phase excitation

When rotating, the synchronizing torque of the 3-phase unit increases as the speed of rotation, against the phase rotation, is increased (Fig. 2). The torque of the single-phase unit, either salient pole or uniform air gap, diminishes as the speed is

1. For all references see list at end of paper.

* Analysis of the uniform air gap type is particularly important when standard, wound rotor, induction motors are applied for duplicate position systems of large power.

increased, with equal effect for either direction of rotation. For these reasons position indicating instruments have salient poles while continuously rotating instruments are most satisfactory with uniform air gaps and 3-phase excitation. However, the salient pole type is sometimes more desirable when the rotation must be in either direction. This is true because the torque with 3-phase excitation diminishes more rapidly as the speed increases, when rotation is in the direction of the phase rotation.

In general, the torque angle curves of the transmitter and the receiver will not coincide for either the salient pole or uniform air gap types with either 3-phase or single-phase excitation (Fig. 3). With 3-phase excitation the curves have the maximum difference at standstill and approach similarity as the speed increases. With single-phase excitation the curves are identical at standstill, diverge as the speed of rotation increases, and approach similarity again as the speed is raised above synchronous speed. They do not have so great a divergence as in the 3-phase case. This is another feature making it sometimes desirable to use salient poles for rotating instruments as the average torque of the transmitter and the receiver, and especially the receiver torque, is greater. This is particularly true when the maximum speed is considerably less than the synchronous speed (under about one-half).

Usually both the transmitter and the receiver draw electrical power from the supply lines. However, above certain speeds electrical power is pumped into the lines by the receiver while the transmitter draws power from the lines (Fig. 4). In this case there is a transfer of electrical power through the system. Mechanical and electrical energy are delivered to the transmitter and both forms of energy compose the output of the receiver.

The ability of Selsyn instruments to hold 2 or more remotely located shafts in synchronism as though they were geared, either at standstill or when continuously rotating, opens up a wide field of application. Heretofore, this field has been limited to those applications which could be filled by mechanical devices such as gears, chains, belts, etc.

The following 3 sections of the paper comprise the general analysis of the instruments and give the formulas for calculating their performance. The results have been substantiated by comparison of calculated and tested performance of the instruments.

Part I—Standstill Torque-Angle Characteristics

Single-Phase Salient Poles

Approximate equations for current and torque may be established directly from synchronous machine theory. However, the following analyses are built up from fundamental laws in order to establish a theory especially adapted to Selsyn instruments, including the important effect of the resistance of the windings.

The method used is to write the vector equations for the primary and secondary circuits according to Kirchoff's laws using the applied voltage as the axis of reference. These equations determine the

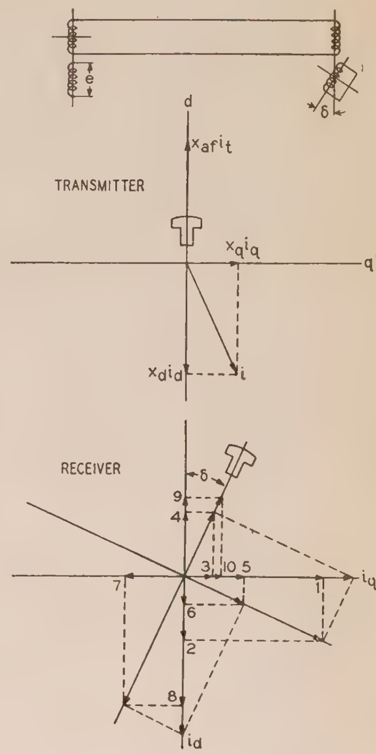


Fig. 5. Equivalent circuit and space diagram of flux linkages for salient pole instruments at standstill

1 = $x_q i_q \cos^2 \delta$
2 = $x_q i_q \sin \delta \cos \delta$
3 = $x_d i_q \sin^2 \delta$
4 = $x_d i_q \sin \delta \cos \delta$
5 = $x_q i_d \sin \delta \cos \delta$
6 = $x_q i_d \sin^2 \delta$
7 = $x_d i_d \sin \delta \cos \delta$
8 = $x_d i_d \cos^2 \delta$
9 = $x_{af} i_r \cos \delta$
10 = $x_{af} i_r \sin \delta$

currents in terms of which the torque is expressed. The magnetomotive forces and flux waves are sinusoidal in space and, therefore, can be split into components along space axes using the sine and cosine as multipliers. Time relations are expressed by complex quantities related to the exciting voltage. Space relations are expressed by simple quantities along 2 axes in space quadrature.

Selsyn instruments of any type, either with 3-phase or single-phase excitation and with salient poles or uniform air gaps, are represented by the circuits of Fig. 1. This is the basic system of one indicating or receiving instrument connected to one transmitting unit. The excited or primary members, in the case of single-phase excitation, may have a short-circuited winding in quadrature with the exciting winding. This may be in the form of a bar winding (amortisseur bars in the pole face) or a winding wound in slots, or a winding formed by short circuiting 2 terminals of a 3-phase wye or delta-connected winding. In the latter case single-phase excitation is applied from one terminal to the other 2 connected together. These forms of quadrature windings are included in Fig. 1. They reduce the quadrature impedance of the secondary winding but this effect may be accounted for in the calculation of the quadrature impedance of Section III. The presence of such windings does not alter the analysis.

The reactance voltage present in the secondary circuits may be expressed by the components illus-

trated in Fig. 5. This figure is a space diagram showing the resolution of the secondary current into components in the axes of symmetry of the 2 machines. When these components are multiplied by the reactance coefficients in the respective axes the reactance voltages in each axis are determined. These voltages are shown in the diagram. The direct space axis is taken as the axis of the primary winding of the transmitter. The quadrature axis is, of course, at right angles to it. The voltages are summed along each axis separately and equated to zero, giving 2 (time vector) equations. All of the nomenclature is listed in the appendix at the close of the paper.

For the direct axis:

$$0 = j(x_d i_d + x_q i_d \sin^2 \delta + x_d i_d \cos^2 \delta + x_d i_q \sin \delta \cos \delta - x_q i_q \sin \delta \cos \delta + i_r x_{af} \cos \delta + i_t x_{af}) + 2r_a i_d \quad (1)$$

For the quadrature axis:

$$0 = j(x_q i_q + x_d i_q \sin^2 \delta + x_q i_q \cos^2 \delta + x_d i_d \sin \delta \cos \delta - x_q i_d \sin \delta \cos \delta + i_r x_{af} \sin \delta) + 2r_a i_q \quad (2)$$

For the primary circuits:

$$e = Z_f i_t + jx_{af} i_d \quad (3)$$

$$0 = Z_f i_r + jx_{af} i_d \cos \delta + jx_{af} i_q \sin \delta + e \quad (4)$$

These equations give the following expressions for the currents:

$$i_d = \frac{jx_{af}e}{B^2 - AC} (B \sin \delta + C - C \cos \delta) \quad (5)$$

$$i_q = \frac{-jx_{af}e}{B^2 - AC} (A \sin \delta + B - B \cos \delta) \quad (6)$$

$$i_t = \frac{1}{Z_f} (e - jx_{af} i_d) \quad (7)$$

$$i_r = - \frac{1}{Z_f} (e + jx_{af}\, i_d \cos \delta + jx_{af}\, i_q \sin \delta) \quad (8)$$

where:

$$A = jZ_f(x_d + x_q \sin^2 \delta + x_d \cos^2 \delta) + x^2_{af} (1 + \cos^2 \delta) + 2r_a Z_f \quad (9)$$

$$B = (jZ_f(x_d - x_q) + x^2_{af}) \sin \delta \cos \delta \quad (10)$$

$$C = jZ_f(x_q + x_d \sin^2 \delta + x_q \cos^2 \delta) + x^2_{af} \sin^2 \delta] + 2r_a Z_f \quad (11)$$

In the majority of applications the displacement angle δ is small. Under these conditions:

$$A = 2(Z_f Z_d + x_{af}^2) \quad (12)$$

$$B = (Z_f Z_d - Z_f Z_q + x_{af}^2) \sin \delta \quad (13)$$

$$C = 2\, Z_f Z_q \quad (14)$$

$$i_q = \frac{jx_{af}\, e\, A \sin \delta}{AC} \quad (15)$$

or

$$i_q = \frac{jx_{af}\, e \sin \delta}{2\, Z_f\, Z_q} \quad (16)$$

and $I = e/Z_f$ = exciting current. (17)

These results, apparent from physical reasoning, are useful in determining the torque for small angles.

It is physically evident and has already been established (eq 19 of reference 2) that the torque is given by:

$$T = I_q \Psi_d - I_d \Psi_q \quad (18)$$

where

$$\Psi_d = x_{af} I + x_d I_d \quad (19)$$

$$\Psi_q = x_q I_q \quad (20)$$

The reference equation for Ψ_q has a term representing quadrature, primary, excitation. Although the general case, including that of a short-circuited primary winding in the quadrature axis is under consideration, the formulas for reactance (Section III) give the combined quadrature impedance for the secondary. Therefore, in case of a quadrature, primary circuit, x_q in eq 20 above must be the reactive component of Z_q', eq 73.

From eqs 18, 19, and 20, the torque is the sum of the scalar products:

$$T = x_{af} I \cdot i_q + x_d i_d \cdot i_q - x_q i_q \cdot i_d \quad (21)$$

For small angles i_d is negligible so that the torque is given by:

$$T = x_{af} I \cdot i_q \quad (22)$$

This is the electrical torque due to the primary and secondary currents. The reluctance torque terms are negligible. Substituting eqs 16 and 17:

$$T = \frac{(jx^2_{af}\, e \sin \delta)}{2\, Z_f\, Z_q} \cdot e/Z_f \quad (23)$$

Taking the scalar product:

$$T = v^2 x_q \sin \delta / 2Z^2_q \quad \text{synchronous watts} \quad (24)$$

where v is the normal secondary voltage ($= jx_{af}e/Z_f$).

The total torque is obtained when line-to-line values for the coefficients of the 3-phase winding are used.

Single-Phase Round Rotor

The formulas are the same as for the salient pole case except that here:

$$Z_a = Z_d = Z_q \quad (25)$$

$$A = 2Z_f Z_a + x^2_{af}(1 + \cos^2 \delta) \quad (26)$$

$$B = x^2_{af} \sin \delta \cos \delta \quad (27)$$

$$C = 2Z_f Z_a + x^2_{af} \sin^2 \delta \quad (28)$$

Three Phase

For this case there is only the one coefficient, Z_a of secondary impedance to be considered. Currents are considered to be established by excitation of one unit only with the primary of the other unit under 3-phase short circuit. Currents are then superposed for simultaneous excitation of both units. As the short circuit of the primary winding is 3 phase there is no displacement angle to be taken into account until superposition is made. All vectors are time vectors.

Voltages appearing in the secondary circuits are:

$$2Z_a i_a + jx_{af}(i_t + i_r) = 0 \quad (29)$$

Voltages appearing in the primary circuits are:

$$e = Z_f i_t + jx_{af} i_a \quad (30)$$

$$0 = Z_f i_r + jx_{af} i_a \quad (31)$$

Solution of these equations gives:

$I_t = A/D$ (32)

$I_r = C/D$ (33)

$I_a = B/D$ (34)

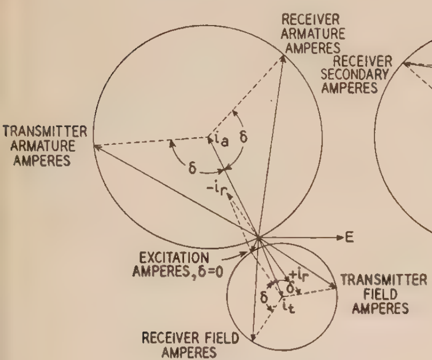
where

$A = 2Z_aZ_f + x_{af}^2$ (35)

$B = -jx_{af}Z_f$ (36)

$C = -x_{af}^2$ (37)

$D = 2Z_f(Z_fZ_a + x_{af}^2)$ (38)



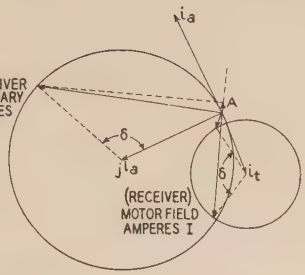


Fig. 6 (left). Time phase vector diagram showing the current loci of 3-phase Selsyn instruments at 7,000 rpm

Fig. 7 (right). Graphical calculation of torque for 3-phase instruments

Torque = (scalar projection of secondary amperes on the field amperes, A) (scalar length of the field amperes) (mutual inductance, x_{af})

With rotation of the transmitter in the direction of the phase rotation the net currents are:

For the transmitting instrument:

$I_t = A/D - C/D\,(\cos\delta - j\sin\delta)$ (39)

$I_a = B/D(1 - \cos\delta - j\sin\delta)$ (40)

For the receiving instrument:

$I_r = A/D - C/D\,(\cos\delta + j\sin\delta)$ (41)

$I_a = B/D(1 - \cos\delta - j\sin\delta)$ (42)

All of the vectors are referred to the excitation voltage.

Since $i_d = i_a$ and $i_q = ji_a$ the torque from eq 21 is:

$T_t = jx_{af}i_a \cdot I_t$ synchronous watts (43)

The receiver torque is:

$T_r = jx_{af}I_a \cdot I_r$ synchronous watts (44)

If the coefficients and exciting voltage are line-to-line values the total torques in inch-ounces are obtained when the results of eqs 43 and 44 in synchronous watts, are multiplied by K where:

$K = (8{,}500\sqrt{3})/2\pi n_s$ (45)

where n_s is the synchronous revolutions per minute. The term, $\sqrt{3}$, becomes 3 if the coefficients and the exciting voltage are line-to-neutral values.

The formulas neglect the core loss but otherwise are the same as would be obtained from the usual induction motor circuit (see reference 3).

The calculations may be made graphically, if desired, by use of the circle diagrams shown in Fig. 6. It is obvious from eqs 39 to 42 that the current loci are circles. In the torque calculation, Fig. 7, the secondary current circle is rotated 90 deg in the direction of the phase rotation. The circumference of each circle is divided into as many divisions as steps of δ are to be taken and the vectors are drawn for each step. For any value of δ, either the primary or secondary vector is scaled as is the perpendicular projection of the other upon it. The product of the 2 measurements is then taken and multiplied by x_{af} giving the torque in synchronous watts. The method is subject to inaccuracy due to the fact that the scalar product is taken at nearly a 90-deg angle for some values of δ. However, it is an excellent method for calculating torque-angle curves since points which are out of line are readily detectable.

N-Unit Systems

When receiving instruments are connected in parallel to a larger transmitter there are a number of variations to be considered.

First there is the case of all receivers being disconnected except one, when the coefficients of the transmitter and receiver will not be alike. In this case there are the coefficients Z_{dt}, Z_{qt}, Z_{dr}, Z_{qr}, Z_{ft}, Z_{fr}, x_{aft}, x_{afr} to be considered in the single-phase case and Z_{at}, Z_{ar}, Z_{ft}, Z_{fr}, x_{aft}, x_{afr} in the 3-phase case. The subscripts t and r indicate the transmitter and receiver respectively. The solution is obtained identifying the coefficients of eqs 1, 2, 3, 4, 29, 30, and 31 by this nomenclature, and proceeding as before.

Secondly, there is the case of similar receivers operating simultaneously with one transmitter. In this case the general nomenclature just given is to be used and all coefficients for the receivers are to be divided by the number of parallel units, n. With these coefficients the current and torque of the transmitter is obtained. The total current for all of the receivers, primary or secondary is n times the current for any one. The torque is likewise n^2 times the torque of any one.

Finally there is the case of unlike receivers in parallel, operating with one transmitter. There is little need for the solution of this case although it is easy to obtain when the coefficients of the transmitter are small compared to those for any receiver. In this case the voltage of the secondary system is taken to be fixed assuming the transmitter to have negligible (zero) impedance. The coefficients for the transmitter drop out of the equations and the equation for the primary circuit of the transmitter vanishes. The remaining equations are solved as before and the results substituted in the expression for torque.

Other variations have been suggested but as yet they have little value and are beyond the scope of this paper.

Part II—Torque-Angle Characteristics With Synchronous Rotation

Single Phase, Salient Poles

When the primary or secondary rotates, relative to the other, with a constant speed of n rpm, the armature current is composed of 2 balanced phase currents rotating with positive and negative phase sequence when n is less than the synchronous revolutions per minute. One moves at the speed $(s + 1)$ and the other at $(s - 1)$ where s is $np/120f$; f is the excitation frequency; and the speed is expressed as a fraction of the synchronous speed $120f/p$.

The balanced 3-phase magnetomotive forces rotating over the poles are resolved into components pulsating with respect to the poles in the 2 axes of symmetry. For example, a secondary current i_f, rotating at speed $(1 + s)$ with the rotor moving at speed s is represented by a pulsating component i_f in the direct axis and by ji_f in the quadrature axis, each component pulsating at normal frequency. Likewise a current i_b, rotating at $(s - 1)$, is represented by components, pulsating at normal frequency, i_b in the direct axis and $-ji_b$ in the quadrature axis. In Fig. 8 these components are shown for both the transmitter and receiver. Since the direct and quadrature space axes are taken as those of the transmitter, the components must be resolved onto the symmetrical axes of the receiver, giving 8 pulsating magnetomotive forces or currents in the axes of the receiver whereas there are only 4 for the transmitter. Each of the components is multiplied by the reactance coefficient of its respective axis, giving components proportional to flux at normal frequency. These components in the receiver are then resolved back into the space axes q and d of Fig. 8 and summed up for each axis. The final components are given in the figure. The summation for the direct axis is:

$$\Psi_d = i_b(x_d + x_d\cos^2\delta + x_q\sin^2\delta) - ji_b(x_d - x_q)\sin\delta\cos\delta + i_f(x_d + x_d\cos^2\delta + x_q\sin^2\delta) + ji_f(x_d - x_q)\sin\delta\cos\delta + x_{af}i_t + x_{af}i_r\cos\delta \tag{46}$$

and for the quadrature axis:

$$\Psi_q = -ji_b(x_q + x_d\sin^2\delta + x_q\cos^2\delta) + i_b(x_d - x_q)\sin\delta\cos\delta + ji_f(x_q + x_d\sin^2\delta + x_q\cos^2\delta) + i_f(x_d - x_q)\sin\delta\cos\delta + x_{af}i_r\sin\delta \tag{47}$$

These are pulsating flux linkages in each axis. They are converted to the rotating components,

$$\Psi_f = (\Psi_d - j\Psi_q)/2 \tag{48}$$

$$\Psi_b = (\Psi_d + j\Psi_q)/2 \tag{49}$$

and are multiplied, respectively, by $j(1 + s)$ and $-j(s - 1)$ to obtain the voltage produced in the secondary at the 2 frequencies. To each is added the (ir) voltage and the sums equated to zero. Two equations result for the secondary circuit:

$$0 = \{4r_a/(1 + s)\}i_f + j\Psi_f \tag{50}$$

$$0 = \{4r_a/(s - 1)\}i_b - j\Psi_b \tag{51}$$

The field or primary equations are,

$$e = Z_f i_t + jx_{af}(i_f + i_b) \tag{52}$$

$$0 = Z_f i_r + jx_{af}(\cos\delta + j\sin\delta)i_f + jx_{af}(\cos\delta - j\sin\delta)\,i_b + e \tag{53}$$

Simultaneous solution of these equations gives:

$$i_f = \frac{jx_{af}\,e}{2(BC - AD)} \times \Big[D(1 - \cos\delta + j\sin\delta) - B\,(1 - \cos\delta - j\sin\delta)\Big] \tag{54}$$

$$i_b = \frac{jx_{af}\,e}{2(BC - AD)} \times \Big[A(1 - \cos\delta - j\sin\delta) - C\,(1 - \cos\delta + j\sin\delta)\Big] \tag{55}$$

$$i_t = \frac{e}{Z_f} - \frac{jx_{af}}{Z_f}(i_f + i_b) \tag{56}$$

$$i_r = \frac{-1}{Z_f}\Big\{e + jx_{af}(\cos\delta + j\sin\delta)i_f + jx_{af}(\cos\delta - j\sin\delta)i_b\Big\} \tag{57}$$

where

$$A = \frac{2r_aZ_f}{1 + s} + jZ_f(x_d + x_q) + x_{af}^2 \tag{58}$$

$$B = \{jZ_f(x_d - x_q) + x_{af}^2\}(\cos^2\delta - j\sin\delta\cos\delta) \tag{59}$$

$$C = \{jZ_f(x_d - x_q) + x_{af}^2\}(\cos^2\delta + j\sin\delta\cos\delta) \tag{60}$$

$$D = \frac{2r_aZ_f}{1 - s} + jZ_f(x_d + x_q) + x_{af}^2 \tag{61}$$

For the transmitter the average torque is the scalar product

$$T_t = jx_{af}(i_f - i_b)\cdot i_t + j\,(x_d - x_a)(i_b + i_f)\cdot(i_f - i_b) \tag{62}$$

and for the receiver:

$$T_r = \{\,jx_{af}i_r + j\,(x_d - x_q)[i_f(\cos\delta + j\sin\delta) + i_b(\cos\delta - j\sin\delta)]\}\cdot[i_f(\cos\delta + j\sin\delta) - i_b(\cos\delta - j\sin\delta)] \tag{63}$$

The torque expressions are immediately apparent from eq 21 where $i_d = (i_f + i_b)$ and $i_q = j(i_f - i_b)$.

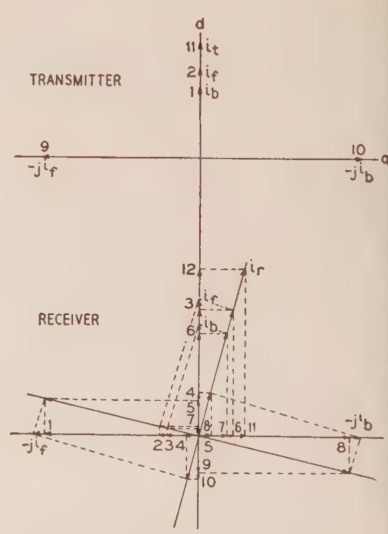


Fig. 8. Space diagram of flux linkages for salient pole instruments under rotation

DIRECT AXIS LINKAGES	QUADRATURE AXIS LINKAGES
1 = i_bx_d	1 = $ji_fx_q\cos^2\delta$
2 = i_fx_d	2 = $-i_fx_q\sin\delta\cos\delta$
3 = $i_fx_d\cos^2\delta$	3 = $-i_bx_q\sin\delta\cos\delta$
4 = $-ji_bx_d\sin\delta\cos\delta$	4 = $ji_fx_d\sin^2\delta$
5 = $-ji_fx_q\sin\delta\cos\delta$	5 = $-ji_bx_d\sin^2\delta$
6 = $i_bx_d\cos^2\delta$	6 = $i_fx_d\sin\delta\cos\delta$
7 = $i_fx_q\sin^2\delta$	7 = $i_bx_d\sin\delta\cos\delta$
8 = $i_bx_q\sin^2\delta$	8 = $-ji_bx_q\cos^2\delta$
9 = $ji_bx_q\sin\delta\cos\delta$	9 = ji_fx_q
10 = $ji_fx_d\sin\delta\cos\delta$	10 = $-ji_bx_q$
11 = $x_{af}i_t$	11 = $x_{af}i_r\sin\delta$
12 = $x_{af}i_r\cos\delta$	(Field) = $x_{af}i_f(\cos\delta + j\sin\delta) + x_{af}i_b(\cos\delta - j\sin\delta)$
(Field) = $x_{af}(i_f + i_b)$	

To determine the torque of the receiver from eq 21 the currents i_f and i_b must first be rotated into the symmetrical axes of the receiver using the operators of eq 53.

In the case of a round rotor, $x_d = x_q = x_a$. For a number of receivers in parallel the solution is made the same as indicated for the standstill case.

Three Phase

The formulas are identically the same as those given for the standstill case where,

$$Z_a = \frac{r_a}{1+s} + jx_a \tag{64}$$

in eq 35 and 38. s is the per unit revolutions per minute and is positive when rotation is in the direction of the phase rotation. For negative rotation the sign of the j terms in eqs 39 to 42, inclusive, must be reversed.

Part III—Reactances

The reactances of Selsyn instruments are the same as those of synchronous machines;[4] accordingly they are calculated by methods established already. As a guide, the basic formulas will be given, omitting the elaboration sometimes used for accurate calculations in design. Each formula for 3-phase windings gives the reactance from line to line with wye connection.

Direct Axis, Line to Line, 3-Phase Reactance

$$x_{ad} = \sqrt{3}\,\omega\ \ \phi_{ad}N_aK_c\,10^{-8}$$

where

ω = $2\pi f$
f = frequency of excitation supply
N_a = turns/phase
K_c = combined pitch and distribution factor
ϕ_{ad} = flux of armature reactance

$$= \frac{2A\ A_{dl}B_g}{F_g}$$

A = peak of armature reaction ampere turns

$$= \frac{4}{\pi}\sqrt{3}\ N_a\ K_c$$

A_{dl} = ratio of maximum density of fundamental flux to maximum density of actual flux when armature is excited with a sine wave magnetomotive force (Fig. 13 of reference 5)
B = maximum density of normal field flux with armature circuit open

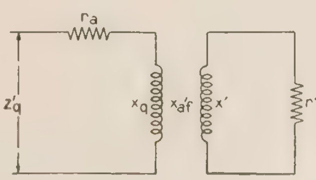


Fig. 9. Circuit for quadrature axis with a short-circuited primary circuit

A_g = area of gap per pole
F_g = normal field, air gap, ampere turns (peak value)

The combined formula is:

$$x_{ad} = \frac{24\omega}{\pi^2}\frac{A_{dl}BA_gN_a^2K_c^2}{F_g}10^{-8}\text{ ohms} \tag{65}$$

Quadrature Axis, Line to Line, 3-Phase Reactance

$$x_{aq} = x_{ad}\left(\frac{1+C_sC_d}{2}\right)K_q \tag{66}$$

where K_q is obtained from Fig. 1 and C_s and C_d are respectively slot and duct coefficients from Fig. 2 of reference 5.

Direct Synchronous Reactance

$$x_d = x_{ad} + x_l \tag{67}$$

where x_l is the leakage reactance[6]

Quadrature Synchronous Reactance

$$x_q = x_{aq} + x_l \tag{68}$$

Single-Phase Field Reactance

$$x_f = \omega\phi N_f10^{-8} = \frac{2\omega}{\pi}\frac{A_{dl}B\ \ A_gN_f^2K_\phi}{F_g}(1+K_l)10^{-8}\text{ ohms} \tag{69}$$

where

N_f = total field turns in series for all poles
K_ϕ = ratio of the area of the actual exciting flux wave to the area of its fundamental (see Fig. 10 of reference 5)
K_l = pole leakage factor (see Fig. 7, Part II of reference 5)

Direct Secondary Impedance

$$Z_d = r_a + jx_d \tag{70}$$

where

r_a = resistance line to line
= 2 times lag resistance

The line resistance may be added to r_a if desired in which case the resistance of one full length line is added.

Quadrature Secondary Impedance

$$Z_q = r_a + jx_q \tag{71}$$

Mutual Reactance Between Primary and Secondary

$$x_{af} = \sqrt{3}\omega\phi K_cN_a\,10^{-8} = \frac{2\sqrt{3}\omega}{\pi}\frac{A_{dl}A_gB}{F_g}N_fN_aK_c\,10^{-8}\text{ ohms} \tag{72}$$

Quadrature Secondary Impedance With a Short-Circuited, Quadrature, Primary Winding

$$Z_q' = \frac{(r_a+jx_q)(r'+jx') + (x_{af}')^2}{(r'+jx')} \tag{73}$$

where

r' = resistance of shorted winding

x' = reactance of shorted winding
x_{af}' = mutual reactance between secondary and shorted primary windings

To determine these coefficients the formulas already given for 3-phase or single-phase windings are applied with a change of constant if necessary to fit the type of winding

The impedance Z_q' will be recognized as that of the circuit of Fig. 9.

PRIMARY IMPEDANCE

$$Z_f = r_f + jx_f \tag{74}$$

Appendix—List of Symbols

(All coefficients for 3-phase windings are line to line)

e = primary, exciting, voltage
i_a = armature or secondary line current
I_d = i_d = direct axis component of i_a
i_b = balanced 3-phase secondary current of phase sequence frequency $(s - 1)$
i_f = balanced 3-phase secondary current of positive phase sequence at $(1 + s)$
I_q = i_q = quadrature axis component of i_a
i_r = primary or field current of the receiver
i_t = primary or field current of the transmitter
I = net primary current of either receiver or transmitter
n = speed of rotation in revolutions per minute
P = number of poles
r_a = armature or secondary resistance
r_f = field or primary resistance
s = per-unit speed of rotation
v = secondary (armature) voltage
x_a = reactance of armature for uniform air gap instruments
x_{ad} = reactance of armature (secondary) reaction in the direct axis for salient pole instruments
x_{aq} = reactance of armature reaction in quadrature axis
x_{af} = mutual reactance between armature (secondary) and field (primary) windings
x_d = total armature reactance in the direct axis
x_f = reactance of field (primary) winding
x_l = leakage reactance of the armature winding
x_q = total armature reactance in the quadrature axis
Z_a = armature (secondary) impedance with uniform air gap
Z_d = direct axis armature impedance = $r_a + jx_d$
Z_f = field (primary) winding impedance = $r_f + jx_f$
Z_q = quadrature axis armature impedance = $r_a + jx_q$
δ = displacement angle between space positions of the rotors
Ψ_d = direct axis secondary flux linkages
Ψ_q = quadrature axis secondary flux linkages

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A Compensated Automatic Synchronizer

A relay for automatically synchronizing rotating machines has been developed which uses vacuum tubes to reduce mechanical adjustments, and which gives the closing indication at a constant time in advance of synchronism. This latter quality is shown to be required for rapid synchronizing with acceptable accuracy, in the absence of extremely accurate speed control. The theoretical requirements of such a synchronizer are derived mathematically in this paper, and a description of a relay which fulfills these requirements is given.

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THE earliest automatic synchronizing probably was done in attended stations. It was not wholly intentional, for the relays had been installed only as protective devices to prevent bad synchronizing; but the operator's confidence increased to the point where it became natural to "pull the button early and let the relay do it."

These early installations provided experience under operating conditions so that the manufacturers felt ready to furnish the necessary synchronizing relays when (about 1922) some systems chose automatic operation for some of their largest units, where the familiar "pull-in" or "self-synchronizing" method would cause disruption of the system. Although different manufacturers produced different designs, most of these early relays appear to have performed only the following basic functions: (1) Prevent giving the closing indication if the average frequency difference exceeded a certain value; and (2) give the closing indication at a fixed angle in advance of synchronism, if the frequency difference permitted giving it at all. The function of bringing about approximate equality of frequency between the 2 sources was performed by separate devices, not treated in this paper.

These relays were adequate for the conditions generally met at the time of their design, and still have the inherent advantages of simplicity and low

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cost which suggest their use on some of the less exacting of present-day installations where the same conditions exist. These conditions are (1) generating units of medium or high reactance, driven by prime movers stable at no load, and (2) tie lines not operating near the stability limit, where synchronizing angles of, say, 30 deg can be tolerated without inconvenience.

However, later experience, particularly with propeller type waterwheels, indicated that it was desirable (1) to vary the closing angle of the relay with the frequency difference so as to compensate for a constant breaker closing time, (2) to minimize the effect of voltage magnitudes on the closing angle and frequency difference setting of the relay, and (3) to increase the accuracy of frequency difference indication by reducing the angular zone in which the average is measured.

Relative Error of Fixed-Angle and Proportional-Angle Synchronizers

The maximum error with the fixed-angle type of relay results when the relative velocity of the 2 vectors is zero at the relay closing angle, but their acceleration a is the maximum possible during the synchronizing period. If the relay closing angle is θ_r and the breaker closing time T seconds, the angular error is

$$\theta_r + \frac{aT^2}{2} \qquad (2)$$

(See appendixes for meaning of symbols and for derivation of equations.)

Feature (1) in the second paragraph preceding requires that the closing indication be given only when the angle θ is decreasing and has the value

$$\theta = sT \qquad (3)$$

where s is frequency difference (hereinafter called "slip" for brevity) in degrees per second, and T is closing time in seconds of breaker plus control relay. This assumes constant closing time, and constant slip during this time; the rate of change of slip at the instant of giving the closing indication might be taken into account, but differences in closing time of the same breaker are difficult to estimate in advance. Variable closing time and variable slip during closure result in angular displacement at the instant the breaker contacts close. Simple means are available to prevent closing if this displacement is excessive and these same means make it unnecessary to take account of rate of change of slip.

Equation 3 shows that the relay closing angle should be advanced proportionally to the slip—a fact familiar to every operator with a little experience in synchronizing. The maximum error with a synchronizer having this characteristic is

$$\pm \frac{aT^2}{2} \qquad (4)$$

It will be seen that this error is less than that of a constant angle synchronizer, by the amount of the constant angle θ_r of the latter. θ_r can be reduced to any reasonable value by suitable refinements, but to do so causes a proportional reduction in the maximum slip at which synchronizing can be accomplished. With erratic prime movers or slow breakers, this decreases the chances of synchronizing almost to zero.

An important fact brought out by these equations is that the difficulty of synchronizing (as measured by the angular errors encountered) increases in proportion to the square of the breaker closing time T. It appears, therefore, that a given percentage decrease in breaker closing time will improve synchronizing conditions more than an equal percentage decrease in acceleration obtained by improved governor adjustment or hydraulic conditions.

Operating Principle

The synchronizer described in this article was designed to meet the 3 requirements stated at the end of the introduction. Its operating principle is described in detail in the following pages, but may be summarized briefly as follows:

1. Phase angle is measured indirectly by measuring the vector difference between machine and bus voltages. (Fig. 1.)
2. The vector difference voltage is rectified to obtain a beat voltage of slip frequency instead of power frequency.
3. The rate of change of this slip-frequency beat voltage is measured by means of a transformer. (Fig. 2, Fig. 12.)
4. This rate-of-change voltage is subtracted from the beat voltage so that the resultant (after filtering out the ripple voltage) will cause a relay operation (through a compensated amplifier) at an angle of advance proportional to slip. (Fig. 12).
5. A circuit is included (Fig. 9) which compensates for differences in voltage magnitudes so that the beat voltage goes through zero (thus permitting synchronizing even at small slips) even if one voltage is above normal and the other below normal.
6. Cut-off (maximum permissible slip for synchronizing) is controlled by a simple instantaneous relay operated from beat voltage, together with an adjustable time auxiliary relay. (Fig. 12.) By this means the error in measurement of cut-off frequency can be reduced to a small value.

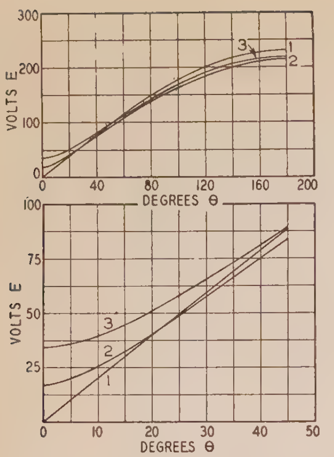
Compensation for Breaker Closing Time

The definite time interval required to allow for breaker closure could be provided by the following combination:

(a) An effect proportional to phase difference and source voltage magnitude.
(b) An effect proportional to slip (or rate of change of phase difference) and source voltage magnitude.

The desired advance time T may be obtained by adjustment of the proportionality factor of one or both, and by opposition of the effects to give a closing indication when (b) overcomes (a).

The first requirement is, then, to find some quantity proportional to phase difference; probably the oldest method of measuring phase difference is the vector difference method, using the "dark lamp" connection. In Fig. 1 is shown the relation between vector difference and phase angle. The condition of minimum bus voltage 0.85 times normal is commonly assumed in the design and application of control apparatus for industrial service, and we might further assume the generator voltage regulated to normal. However, the requirements for unattended installations are more severe, and operating limits of 0.8 to 1.1 times normal have usually been as-



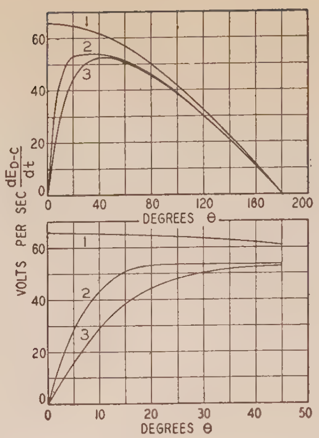


Fig. 1 (left). Vector difference versus phase angle

See eq 5 of appendix for definiton of E

Curve	Machine Voltage	Bus Voltage
1	Normal	Normal
2	Normal	0.85 Normal
3	1.1 Normal	0.8 Normal

Fig. 2 (right). Rate of voltage change versus phase angle. (slip = 36 deg per sec)

See eq 7 of appendix for definition of volts per second
See subcaption of Fig. 1 for meaning of curves 1, 2, and 3

sumed in this service. Figure 1 therefore shows the relation for each of these assumptions.

The next step is to produce a voltage proportional to slip, or to the rate of change of phase angle, which is simpler because we already have a quantity (vector difference) roughly proportional to phase angle and we need only measure its rate of change. However, the vector difference voltage is not of slip frequency, but of power frequency and is, therefore, not directly useful for our purpose. This difficulty can be overcome by rectifying and filtering the vector difference voltage, after which its rate of change is nearly proportional to the rate of change of phase angle (neglecting the ratio error of the rectifier, and the phase shift of the filter at slip frequency).

Assuming sinusoidal voltages, the form factor is 1.11, so the rectified but unfiltered vector difference voltage E_{d-c} at any angle (average value over a period of one cycle at power frequency) is 0.9 of the corresponding value shown in Fig. 1. The filter used in this application begins with a resistance much larger than that of the rectifier load, so the effect of the filter on the average value of voltage may be neglected. In Fig. 2 is shown the rate of change of this average at a slip of 36 deg per sec or 0.1 cycle per sec.

We may assume that this rate of change is measured in some manner which introduces a constant k such that with equal a-c voltages on the 2 sources being synchronized, the rate of change voltage $\frac{k\, dE_{d-c}}{dt}$ equals the d-c phase difference voltage itself at the maximum desired closing angle θ. If this equality is adjusted at 45 deg when operating at a slip

$$s = \frac{\theta}{T} = \frac{45}{T} \text{ (see eq 3)}$$

$$\text{then } k_{45\,\text{deg}} = 1.05\,T \tag{8}$$

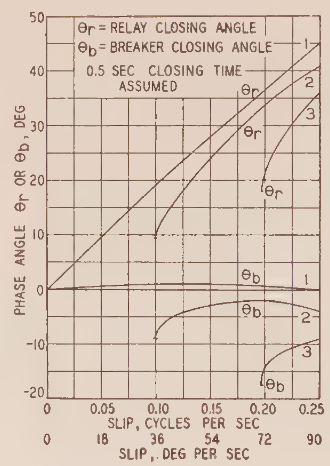
k is calculated for 45 deg because this is judged to be the largest angle of advance that will be required in any ordinary application. A breaker time of 0.5 sec is chosen as being slightly greater than average. These 2 values together determine 0.25 cycles per sec as the maximum permissible slip for synchronizing. However, these values are chosen only for illustration and will change from one installation to another.

In Fig. 3 are shown the relay closing angles θ_r and breaker closing angles θ_b calculated on the basis of a breaker closing time of 0.5 sec, for which $k = 0.5 \times 1.05 = 0.525$. The breaker closing angles are derived from the relay closing angles by the relation $\theta_b = \theta_r - sT$, assuming constant slip during breaker closure.

It will be noted that if the voltages are unequal there is a zone around zero slip, within which synchronizing cannot occur. The limits of this zone are at positive and negative slips

$$s = \frac{M^2 - B^2}{MB\,\pi\,K} \tag{10}$$

and are at the left ends of the curves for conditions 2 and 3 in Fig. 3.



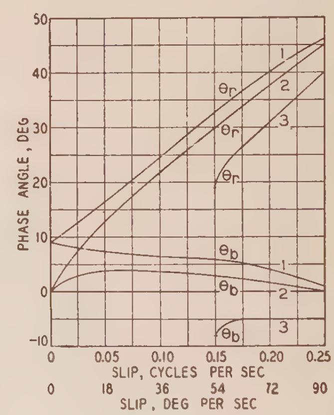


Fig. 3 (left). Theoretical characteristics of uncompensated vector difference synchronizer

See eq 9 of appendix for meaning of sin θ
See subcaption of Fig. 1 for meaning of curves 1, 2, and 3

Fig. 4 (right). Theoretical characteristics of vector difference synchronizer, compensated by constant bias for voltage inequality of 0.15 normal

See subcaption of Fig. 1 for meaning of curves 1, 2, and 3

If synchronizing must be performed down to practically zero slip with a voltage difference $M - B = C$ then a constant bias $0.9C$ may be subtracted from E_{d-c} so that the resultant will pass through zero at

zero degrees for this particular value of difference in magnitudes; this requires a readjustment of k.

The results of a graphic determination of characteristics under these conditions are given in Figs. 4 and 5, for the same assumed voltages and closing time as Fig. 3. (See Fig. 19 in appendix, for method.)

Compensation for Voltage Difference

A more flexible means of compensating for various differences in voltage magnitudes is to subtract from the rectified vector difference a d-c voltage which equals this rectified vector difference at zero degrees. The necessary d-c voltage may be obtained economically (see Fig. 6) by rectifying each of the voltages, opposing them against each other, and filtering them to remove the effect of phase angle. In order to make use of the difference between the voltages, it is necessary to shunt each rectifier by a resistor to pass the reverse current.

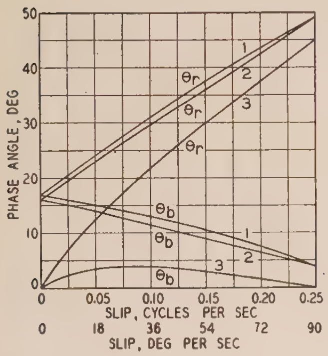


Fig. 5. Theoretical characteristics of vector difference synchronizer compensated by constant bias for voltage inequality of 0.3 normal

See Figs. 1 and 3 for meaning of curves and symbols

The polarity of this resultant still depends upon which source voltage is higher, so the desired effect is obtained only for a difference in one direction, and the opposite effect results from a difference in the other direction. It is therefore necessary to rectify the resultant, as indicated in Fig. 6, thus obtaining a d-c voltage of fixed polarity and of magnitude proportional to the arithmetical difference between the voltages.

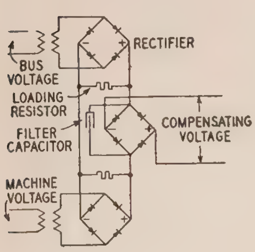


Fig. 6. Circuit for automatic compensation for voltage inequality

Subtracting this inequality voltage from the vector difference voltage, the resultant is always zero at zero degrees, no matter whether the voltage inequality is zero or a larger value.

The possible inoperative zone near zero slip (defined by eqs 10 and 11) is thus eliminated. The characteristics calculated graphically for this connection with the same assumed voltage and closing time are given in Fig. 7.

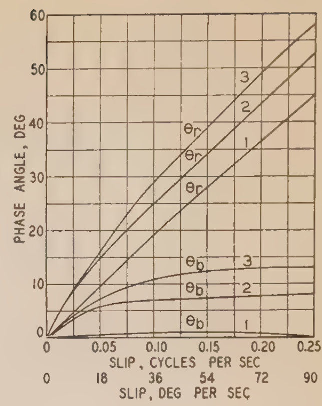


Fig. 7. Theoretical characteristics of vector difference synchronizer automatically compensated for voltage inequality

See Figs. 1 and 3 for meaning of curves and symbols

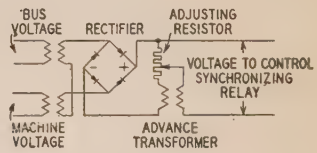


Fig. 8. Circuit for constant advance time (proportional advance angle)

Adjustment of Advance

Having found a system of connections which gives satisfactory theoretical advance characteristics, it is necessary to find a practical means of measuring the rate of change of E_{d-c}. This may be done by means of an "advance transformer" as shown in Fig. 8. The primary reactance at the frequencies to be transmitted is made small in comparison with the resistance of the primary circuit, so the primary current varies at a rate practically in proportion to the rate of change of E_{d-c}. The magnetic circuit of the transformer has a fixed series air gap to minimize the effects of permeability changes and hysteresis. Therefore, the flux varies at a rate practically in proportion to the rate of change of primary current and thus approximately in proportion to the rate of change of E_{d-c}. The induced secondary voltage then indicates the rate of change of E_{d-c}.

Factor k determines the advance time and should be adjustable to conform with different circuit breaker closing times. However, an equivalent effect may be obtained, and the use of high resistances avoided, by connecting a potentiometer resistor across E_{d-c}. Moving the tap on this resistor changes the proportionality factor $\left(\frac{1}{k}\right)$ of E_{d-c} and thus increases or decreases the advance time. The resistor may be calibrated with permanent markings corresponding to various values of advance time, to facilitate field adjustment.

Filter System

The voltage appearing across the output terminals of the advance network may be considered to include 2 parts—one (desired) component of slip frequency with the associated direct current and harmonics;

and the other (undesired) ripple component of twice power frequency with its harmonics. The advance transformer amplifies the ripple frequency component several times as much as it does the slip frequency component, the ratio of the 2 amplifications being approximately equal to the ratio of the 2 frequencies, which is never less than 200:1 in the operating zone.

The ripple component is then several times the slip frequency component at the output terminals of the advance network, and this ripple frequency voltage must be attenuated to a negligible value before applying the combined voltages to a relay; otherwise the relay will buzz at ripple frequency instead of operating at a definite point in the slip frequency cycle.

The basic filter element is of the form shown in Fig. 9, where the series impedance shown may be either predominantly resistive or inductive. In the present case, the resistance of the advance transformer secondary winding serves as the series element of the first section of the filter. The ratio of output to input for one stage is $A = \frac{X_c}{(X_R - X_c)^2 + R^2}$, and for N stages it is A^N. The phase shift for one stage at the transmitted frequency is

$$\theta = \tan^{-1} \frac{R}{X_c - X_R}$$

and for N stages it is

$$\theta = N \tan^{-1} \frac{R}{X_C - X_R} \tag{12}$$

The phase shift is the only source of error introduced by the filter, since the relay operation is to occur at zero voltage and this is not changed by a decrease in amplitude.

Equation 12 shows that the phase shift for the transmitted frequency would be zero if the resistance

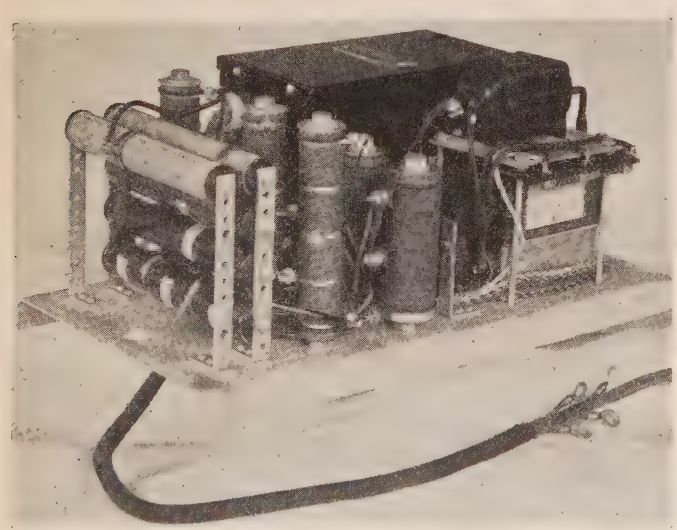


Fig. 10. Auxiliary box, cover removed

of the circuit were zero, but a reactor of the necessary high reactance would be expensive to construct with small enough resistance to reduce the phase shift to an acceptable value. However, the attenuation increases exponentially with the number of stages, while the phase shift increases only in proportion to the number of stages, so by using a multistage filter, it is possible to get the necessary attenuation at ripple frequency by means of an inexpensive resistance-capacitance filter and yet keep the phase shift of the slip frequency down to a small value.

The auxiliary assembly with cover removed is shown in Fig. 10. This includes the insulating transformers, rectifiers, loading and adjusting resistors, advance transformer, and filter.

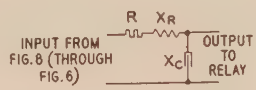


Fig. 9. Filter element

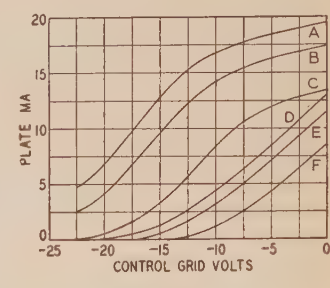


Fig. 11. Effect of source voltage changes on tube characteristics

Plate load = 6,000 ohms

Curve	Tube	Filament Volts	Plate Volts	Screen Volts
A	233	2.2	137.5	137.5
B	233	2	125	125
C	233	1.6	100	100
D	112A	5.5	137.5	
E	112A	5	125	
F	112A	4	100	

Compensated Amplifier

In order that the advance transformer may be of reasonable size and cost, and may require only a small amount of energy from the network generating the slip frequency voltage, it is necessary to use a very large number of turns of fine wire in the secondary; this gives a high secondary resistance. The cost of the filter is decreased by the use of small capacitances, but this also necessitates a high resistance per stage of filter.

The total resistance of these elements is such that they cannot transmit (at the voltage available at the operating point) sufficient power to actuate with the necessary accuracy any purely electromechanical relay. A tube amplifier may be interposed but it must be compensated for variations in filament and plate voltage, and protected so that its failure will not cause undesired operations.

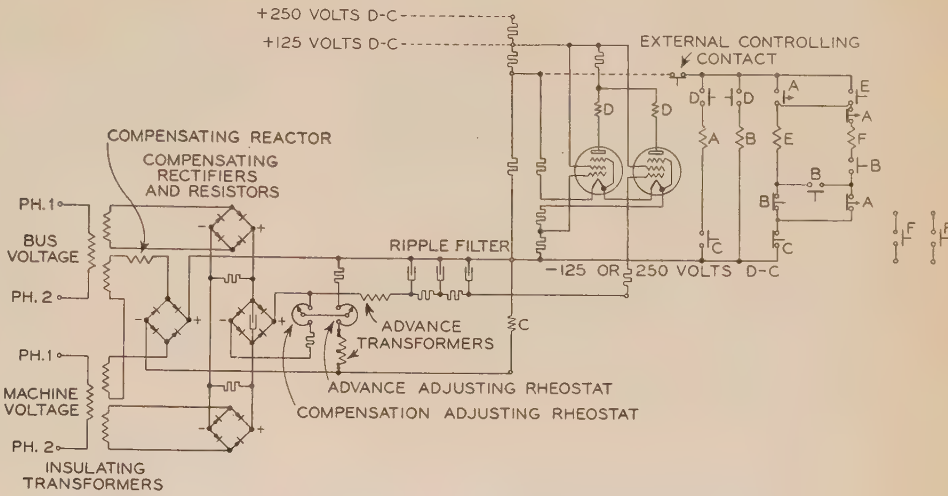
In Fig. 11 is shown the change in tube characteristics, caused by changes in plate and filament source voltage from 0.8 to 1.1 normal. Normal plate voltage is assumed to be 125 volts because that is the value usually available for operation of the circuit breaker.

These curves show that changes of the assumed magnitude in plate and filament voltages will cause as great a change in plate current as would a large change of voltage on the control grid. The changes

in plate current are not in direct proportion to the source voltage, so the most accurate method of compensation seems to be the use of 2 similar tubes in a balanced arrangement, both supplied from the same source. The tubes may be made to actuate a "plate difference" relay (D in Fig. 12) responsive to the difference in plate current.

Fig. 12. Connection diagram of automatic synchronizer

A. Auxiliary cut-off relay
B. Auxiliary relay for D
C. Cut-off relay
D. Differential relay
E. Set-up relay
F. Final auxiliary relay

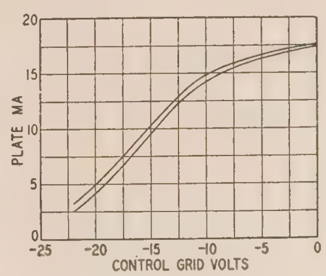


The characteristics, under similar conditions, of 2 tubes of similar rating purchased at different times and not purposely matched, are shown in Fig. 13. It will be seen that the difference between plate currents in the normal operating range is equivalent to that caused by a difference of about 0.6 volts on the grids. This difference can be compensated for by means of a slight bias in the adjustment of the differential relay D.

If the control grid of the control tube is allowed to become positive it acts as a plate and since its current must flow through a high resistance, its voltage no longer corresponds to the open circuit voltage of the source. In order to prevent this, it is necessary to apply a bias to the grid so that up to and somewhat beyond the operating point the grid will be negative and the grid current will be negligible. Bias batteries are objectionable because their internal resistance increases gradually so that operation becomes unstable and periodic replacement is necessary. This bias therefore is obtained by means of the voltage drop due to the filament currents flowing through a resistor to negative.

Fig. 13. Difference in characteristics of 2 type 233 tubes chosen at random

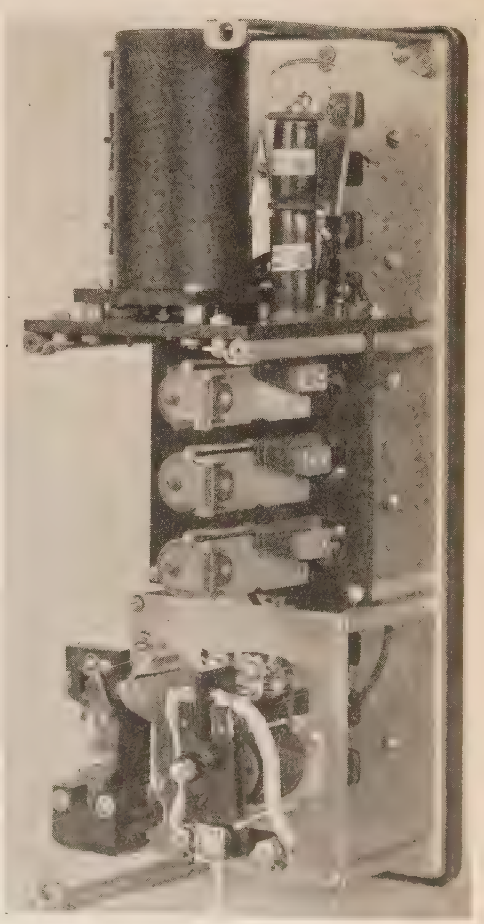
Filament voltage = 2 volts
Plate voltage = 125 volts
Screen voltage = 125 volts
Plate load = 6,000 ohms

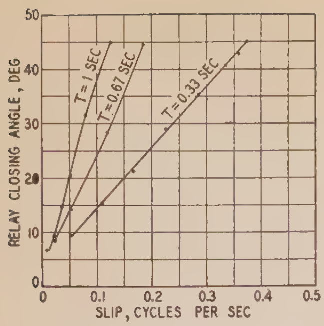


The filaments are connected in series so that if either tube has burned out or been withdrawn, relay D will not be actuated and no synchronizing will take place. This series connection places the filaments at different potentials, tending to unbalance the plate currents, but this is compensated for and balance is restored by connecting the grid of the tube with more positive filament to a tap on the bias resistor.

This compensation is so complete that the grid voltage at which relay D operates is the same within 0.4 volt for d-c control voltages from 100 to 140

Fig. 14. Synchronizing relay, cover removed





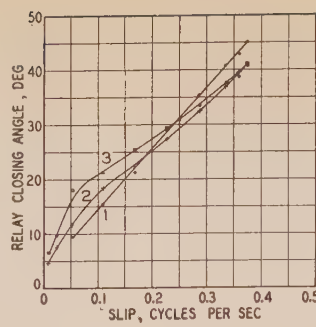


Fig. 15 (left). Test characteristics of synchronizer at equal machine and bus voltages when adjusted for various breaker closing times

Fig. 16 (right). Test characteristics of synchronizer under various voltage conditions when adjusted for 0.33-sec breaker closing time

Curve 1. Normal voltages (N)
Curve 2. Machine voltage, N; bus voltage, 0.85 N
Curve 3. Machine voltage, 1.1 N; bus voltage, 0.8 N

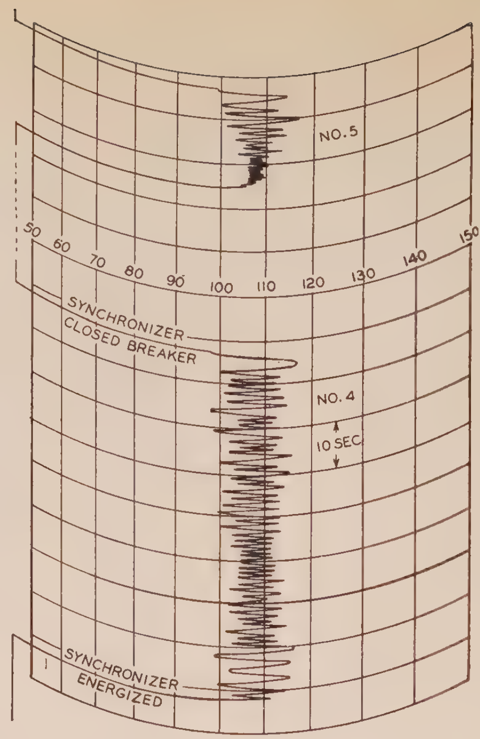
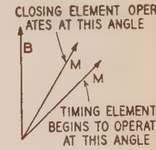


Fig. 17 (left). Synchronizing as recorded by graphic voltmeter across vector difference of machine voltage and 0.1 bus voltage (to keep within scale limits)

Fig. 18 (below). Vector relations in a constant-angle synchronizer



volts. The error introduced by this is negligible, especially in comparison with the effect of changes in breaker closing time due to these same changes in control voltage. However, it would be undesirable to have the relay operate later at low control voltages.

Relay System

Having produced a relay operation at the desired interval in advance of the instant of synchronism, some means is still required for preventing operation when the slip is excessive. This is necessary because (1) even perfect synchronizing at high slip causes large current rushes due to the mechanical inertia of the synchronous machines on the 2 sources; (2) the advance angle of the synchronizer falls below the desired value at large angles and slips; and (3) the angular error due to a given change in breaker time is proportional to slip.

This function may be performed by a simple undervoltage relay (*C* in Fig. 12) actuated by the rectified vector difference voltage.

Relay *B* has not sufficient contact capacity for most circuit breaker closing relay coil circuits, so an internal auxiliary relay (*F* in Fig. 12) is used. This has two electrically separate circuits each capable of closing and carrying 18 amp.

If relay *F* were controlled only by relays *B*, *C*, and *A*, it would be possible to obtain late closures around the limiting value of slip; because relay *B* could operate at the desired angle but relays *C* and *A* might close possibly 0.15 sec later and *F* would still close. This is prevented by relay *E*, which is connected through the checking contacts of relay *B*, so that it must be picked up by relays *C* and *A* before relay *B* operates, or else it cannot pick up until relay *B* has reset again.

The assembled synchronizing relay is shown in Fig. 14. The auxiliary box is mounted on the relay mounting studs behind the board, and connected to the relay connection studs by a cable with each lead cut to the proper length. All panel wiring runs to the relay studs, and none to the auxiliary box.

Over-All Characteristics

Characteristics of the assembled relay when adjusted for 3 different breaker closing times are shown in Fig. 15. In Fig. 16 are shown the characteristics when adjusted at normal voltage for one value of breaker closing time, and then subjected to the other voltage conditions previously assumed. These results were obtained with a phase shifter driven by a d-c motor with speed control by adjustment of armature voltage. The advance time was measured by a cycle counter connected to be started by the synchronizing relay and stopped at zero phase angle by a gas or mercury vapor hot cathode electronic tube triggered by a passing contact on the phase shifter.

Field Tests

A basically similar design of automatic synchronizer showing about the same accuracy in factory test was tested with automatic switching equipment on a waterwheel driven generator rated 2,250 kva, 2,300 volts, 505 amp, 138.5 rpm.

The waterwheel was of the propeller type, operating at 20 ft head. Its no load speed was somewhat unsteady, as shown by Fig. 17, in which each point of maximum and minimum voltage corresponds approximately to 180 deg and 0 deg, respectively.

The synchronizer and speed matcher were held out of circuit until the mechanical timer on the (Woodward) governor had released. The unit required about 30 sec to come to synchronous speed, and each test was begun at low speed, probably less than 0.1 normal. The breaker closing time was 0.45 to 0.5 second.

Synchronizing angles were read by close observation of the synchroscope but are probably subject to considerable errors in reading. Current read was the maximum swing indicated on a switchboard ammeter (800-amp scale). Since this was easier to read, and since the machine and bus voltages were well balanced at the time of the test, these currents are a more accurate indication of performance.

The poorest shot (45 deg late) was caused by the slip increasing to a high value after approaching zero phase angle at a very small value; this could not be prevented by the synchronizer because it occurred after the correct closing indication had been given. Where necessary, however, it might be prevented by an additional relay to take advantage of the trip-free characteristics of the synchronizing breaker.

Summary

In the absence of extremely accurate speed control, rapid synchronizing with acceptable accuracy requires giving the closing indication at a constant time (rather than a constant angle) in advance of synchronism. System conditions may cause a difference in magnitude of the voltages of the 2 sources, and synchronizing should still take place under these conditions.

A relay has been developed which meets the above requirements and which does not require numerous or delicate field adjustments. Mechanical adjustments have been reduced to a minimum by the use of vacuum tubes, which have been applied in such a way that if a tube has failed no operation can occur. The arrangement compensates automatically for the effects of both source and control voltage variations, on the relay.

Table I—Field Tests on Automatic Synchronizer

Test No.	Time Seconds	Angle Degrees	Early, Late or Backing	Fast or Slow Direction	Amp
1	35	5	E	S	10
2	45	10	L	F	180
3	35	0		S	0
4	120	0		F	20
5	40	30	B	S	450
6	45	5	L	S	110
7	45	0		S	75
8	40	5	E	F	10
9	45	20	B	S	350
10	40	10	L	F	150
11	30	0		F	0
12	30	0		F	0
13	40	5	L	F	90
14	90	10	E	F	100
15	55	5	E	S	110
16	50	0		F	0
17	50	0		F	20
18	40	10	L	S	150
19	50	10	E	S	110
20	55	0		F	80
21	55	15	E	S	150
22	50	45	L	F	550
23	45	15	E	S	140
24	45	15	B	S	160
Avg	49	10			125

The 3 backing shots apparently resulted from the slip reversing its sign after entering the synchronizing zone at a value above cut-off and before zero phase angle was reached; these unexpected conditions do not cause false operation with the design covered by this paper.

Appendix A—Symbols

a = relative acceleration of the 2 voltage vectors, in degrees per degree per second

B = bus voltage

E = vector difference between machine and bus voltages

E_1 = machine and bus voltage, when of equal magnitude

E_{d-c} = rectified vector difference voltage

k = advance transformer secondary voltage divided by $\frac{dE_{d-c}}{dt}$

K = 0.00555 k

M = machine voltage

s = frequency difference (slip) in degrees per second (= 360 times frequency difference in cycles per second)

s_m = maximum permissible (constant) slip for synchronizing

s_r = slip at θ_r

t = time setting of timing relay of a constant angle synchronizer, seconds (timing element must close ahead of θ_r to permit synchronizing)

T = closing time of control relay and breaker, seconds

θ = phase angle between machine and bus voltages

θ_r = θ at the instant when the synchronizing relay starts to close the breaker

θ_t = θ at the instant when the timing element of a constant-angle synchronizer begins to operate

Appendix B—Derivation of Equations

Error of Constant Angle Synchronizer

The relay elements are assumed to be adjusted so that the breaker contacts close at zero phase angle when operating at a constant slip equal to s_m, so

$\theta_r = s_m T$ (See Fig. 18)

Also, for this condition $\theta_t - \theta_r = s_m t$

since the timing element must close at or before θ_r in order to permit synchronizing

Therefore $(\theta_t - \theta_r)/t = s_m$

and $(\theta_t - \theta_r)T/t = \theta_r$

One limiting condition is where the slip at θ_r is the maximum value permitted by the settings of θ_r, θ_t, and t, and where a is at its maximum value (s increasing) and remains so. For this condition, the slip at θ_t is

$s_r - at$,

the average slip between θ_t and θ_r is

$$\frac{s_r + (s_r - at)}{2} = s_r - (at/2)$$

and $\theta_t - \theta_r = [s_r - (at/2)]\, t = s_r t - at^2/2$

so $s_r = [(\theta_t - \theta_r)/t] + (at/2)$

Average slip during time T is

$s_r + (aT/2) = ((\theta_t - \theta_r)/t) + (at/2) + (aT/2)$

and the angle during time T is

$[(\theta_t - \theta_r)\ T/t] + (atT/2) + (aT^2/2)$

Since $(\theta_t - \theta_r)\ T/t = \theta_r$, and the closing indication is given at θ_r, the error in degrees late at the instant of breaker contact closure is

$[(\theta_t - \theta_r)\ T/t] + (atT/2) + (aT^2/2) - [(\theta_t - \theta_r)\ T/t]$,

which is $(atT/2) + (aT^2/2)$ (1)

The term $(aT^2/2)$ is due to the acceleration while the breaker is closing, and cannot be decreased by adjustment of the relay. The term $(atT/2)$ is due to part of the acceleration while the slip is being measured and is practically always smaller than the other term, but is difficult to reduce below a small value wh ch depends on the operating principle and construction of the timing element.

The other limiting condition is where the slip at θ_r is zero but the acceleration is at its maximum and of such sign as to cause the phase angle to increase instead of decreasing from this point. The angle traversed during time T is then $\frac{aT^2}{2}$ and the error is

$$+\frac{aT^2}{2} \tag{2}$$

The errors resulting from the 2 limiting conditions are equal when $(atT/2) + (aT^2/2) = \theta_r + (aT^2/2)$ or $atT/2 = \theta_r$

Assuming reasonable values such as

$\theta_r = 30$ deg, $t = 0.2$, $T = 0.5$, then

$a = 600$ deg per sec per sec, so it is obvious that the largest errors with a fixed angle synchronizer will be experienced with the backing shots covered by the second case.

Maximum Probable Error of Proportional Angle Synchronizer

Closing angle of relay $\theta_r = sT$ (3)

Average slip during time $T = s \pm \frac{aT}{2}$

Angle traversed during time $T = sT \pm \frac{aT^2}{2}$

Error in degrees $= sT \pm \frac{aT^2}{2} - sT$

$$= \pm \frac{aT^2}{2} \qquad (4)$$

Vector Difference Voltage

From trigonometry

$$E = \sqrt{M^2 + B^2 - 2MB\cos\theta} \qquad (5)$$

Average Value of Rectified Voltage

Average value of a-c voltage =

$$\frac{1}{1.11}\sqrt{M^2 + B^2 - 2MB\cos\theta} = 0.9\sqrt{M^2 + B^2 - 2MB\cos\theta} \qquad (6)$$

(where 1.11 = form factor for a sine wave)

Rate of Change of Rectified Voltage

$$\frac{d}{d\theta}E_{d-c} = \frac{d}{d\theta}0.9\sqrt{M^2 + B^2 - 2MB\cos\theta}$$

$$= \frac{0.9\,MB\sin\theta}{\sqrt{M^2 + B^2 - 2MB\cos\theta}} \text{ in volts per radian}$$

Since one radian $= \frac{360 \text{ deg}}{2\pi}$

$$\frac{d\,E_{d-c}}{d\theta} = \frac{1.8\pi}{360}\frac{MB\sin\theta}{\sqrt{M^2 + B^2 - 2MB\cos\theta}} \text{ in volts per degree}$$

$\frac{d\theta}{dt} = s$ in degrees per second

$$\frac{dE_{d-c}}{dt} = \frac{dE_{d-c}}{d\theta}\frac{d\theta}{dt}$$

$$= \frac{0.005\,\pi\,sMB\sin\theta}{\sqrt{M^2 + B^2 - 2MB\cos\theta}} \qquad (7)$$

Derivation of k_{45deg}

$$\frac{0.005\,k\,\pi sMB\sin\theta}{\sqrt{M^2 + B^2 - 2MB\cos\theta}} = 0.9\sqrt{M^2 + B^2 - 2MB\cos\theta}$$

at the operating point of the relay.

$0.005\,k\,\pi s\,MB\sin\theta = 0.9\,(M^2 + B^2 - 2MB\cos\theta)$

$0.005\,k\,\pi\,\theta\,MB\sin\theta = 0.9\,T\,(M^2 + B^2 - 2MB\cos\theta)$

$$k = \frac{180T\,(M^2 + B^2 - 2MB\cos\theta)}{\pi\,\theta MB\sin\theta}$$

Assuming $M = B = E$

$$k = \frac{180T\,(2E^2 - 2E^2\cos\theta)}{\pi\,\theta E^2\sin\theta}$$

$$= \frac{360T}{\pi\,\theta}\,\frac{1-\cos\theta}{\sin\theta}$$

At 45 deg,

$$k = \frac{360T}{45\pi}\,\frac{0.2929}{0.7071}$$

$$= 1.05T \qquad (8)$$

Equation for Closing Angle

$$\frac{0.005\,k\pi sMB\sin\theta}{\sqrt{M^2 + B^2 - 2MB\cos\theta}} = 0.9\sqrt{M^2 + B^2 - 2MB\cos\theta}$$

at the operating point of the relay.

$0.00555\,k\pi sMB\sin\theta = M^2 + B^2 - 2MB\cos\theta$

Let $0.00555\,k = K$

$(M^2 + B^2) - \pi KsMB\sin\theta = 2MB\cos\theta$

Squaring, substituting $(1 - \sin^2\theta)$ for $\cos^2\theta$, and simplifying,

$$(M^2 - B^2)^2 - 2(M^2 + B^2)\,\pi KsMB\sin\theta + (\pi^2K^2s^2 + 4)M^2B^2\sin^2\theta = 0$$

Solving the quadratic,

$$\sin\theta = \frac{(M^2+B^2)\pi Ks \pm \sqrt{(M^2+B^2)^2\pi^2K^2s^2 - (M^2-B^2)^2(\pi^2K^2s^2+4)}}{(\pi^2K^2s^2 + 4)\,MB} \qquad (9)$$

If $M = B = E_1$

$$\sin\theta = \frac{2E_1^2\pi Ks \pm \sqrt{4E_1^4\pi^2K^2s^2 - 0}}{(\pi^2K^2s^2 + 4)E_1^2}$$

$$= \frac{2\pi Ks \pm 2\sqrt{\pi^2K^2s^2}}{\pi^2K^2s^2 + 4}$$

$$= \frac{4\pi Ks}{\pi^2K^2s^2 + 4}$$

Limits of Slip Defining Inoperative Zone

Synchronizing will not occur if the term under the radical in eq 9 is negative, so the minimum slip for synchronizing may be found by setting the term equal to zero

$(M^2 + B^2)^2\,\pi^2K^2s^2 - (M^2 - B^2)^2\,(\pi^2K^2s^2 + 4) = 0$

$(M^4 + 2M^2B^2 + B^4)\,\pi^2K^2s^2 - (M^4 - 2M^2B^2 + B^4)\,(\pi^2K^2s^2 + 4) = 0$

$4M^2B^2\pi^2K^2s^2 - 4(M^2 - B^2)^2 = 0$

$$s = \frac{M^2 - B^2}{MB\pi K} \qquad (10)$$

Angular Limits of Inoperative Zone

Since the term under the radical in eq 9 is zero for this condition,

$$\sin\theta = \frac{(M^2 + B^2)\,\pi Ks}{MB\,(\pi^2K^2s^2 + 4)} \qquad (11)$$

Graphic Determination of Operating Points

Using Fig. 4 as an example,

M = 115 volts

B = 97.7 volts

$C = M - B$ = 17.3 volts

Constant bias = $0.9C$ = 15.5 volts

In Fig. 19 is shown curve 2 of Fig. 1 multiplied by 0.9 and replotted 15.5 volts lower.

Determination of K

E_{d-c} at 45 deg = 0.9 × 83.5 = 75 (from Fig. 1, curve 2)

E_{d-c} compensated = 75 − 15.5 = 59.5

$\frac{d\,E_{d-c}}{dt}$ (at θ = 45 deg and S = 0.1) = 53.7 (from Fig. 2, curve 2)

$\frac{d\,E_{d-c}}{dt}$ (at θ = 45 deg and S = 0.25) $= \frac{0.25}{0.1}\,53.7 = 134$

$$k = \frac{E_{d-c} - C}{\frac{dE_{d-c}}{dt}} = \frac{59.5}{134} = 0.444$$

In Fig. 19 is shown curve 2 of Fig. 2 multiplied by Sk for 5 values of S. The intersections of these 5 curves with the main curve of $(E_{d-c} - 0.9C)$ are the desired operating points at this value of slip.

The other 2 curves in Fig. 4 are obtained in a similar manner using the same values of C and k.

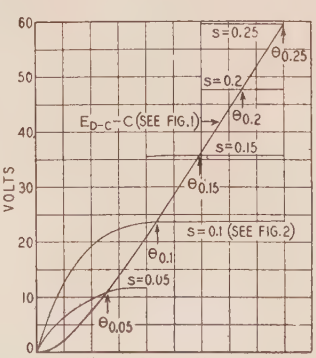


Fig. 19. Graphic determination of operating points θ

Curves marked s are $k\frac{dE_{d-c}}{dt}$

High Voltage Insulators

In this description of the manufacturing processes for suspension insulators, from design and research to finished product, is given a comprehensive list of the laboratory equipment required for adequate testing. Methods of testing for defects and the manner of assembly are sketched, and the need for further standardization is mentioned.

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THE FUNCTION of an insulator is to support an energized conductor at a certain operating voltage without complete internal or external failure for a certain minimum or indefinite period. In doing so it must not involve any localized corona or surface discharges which would create radio interference in nearby receivers. In order that the insulator may be capable of the above, it must pass through an orderly procedure of research, design, and manufacturing.

Research

This stage may be either for the purpose of developing an entirely new type of insulator or to bring about certain desirable revisions in an existing type. Research may be divided into 3 classes:

1. Review of service records, experiences, and troubles in the field.
2. Study of publications on tests, experiments, and research.
3. Investigations by laboratory and field studies.

From the first class we secure much valuable information, coming mostly from the operating sources. The information thus obtained is thoroughly reliable, and much time and money has been spent to obtain and classify it. It is necessary, however, to recognize that the value of this may be limited for one or more of the following reasons: investigation only incidental to operation or regular work; lack of time and equipment; influence of commercial aspect; difficulty in securing all facts; or little opportunity to make comparisons with similar data. The correction of these undesirable conditions, and the closer coöperation of operators and manufacturers in the collection and analysis of field data, will serve greatly in perfecting insulator designs for operating service.

In the second class, involving a study of publications and private records, there is a very helpful fund of information, a study of which gives the investigator a running start and suggests many ideas, some quite opposed to others.

The third class, namely investigations by laboratory and field studies, is the generally accepted idea of research. In this the proper personnel and equipment is necessary to obtain dependable results and minimize erroneous conclusions.

In insulator research not only are electrical engineers necessary, but also mechanical and ceramic engineers, metallurgists and chemists, whose responsibilities consist of making investigations of all materials and combinations of materials entering into insulator manufacture. As an example, an oil-filled bushing may have as many as 15 or 20 different materials in its assembly. At some time all of these must have been investigated and analyzed. In order to do this properly, facilities which should be a part of the factory require the principal items of equipment given here.

Ceramic Laboratory

1. For the testing and investigation of raw materials: ovens, furnaces, standard screens, and other apparatus for physical tests.

2. For ceramic trials: ball mills, blungers, lawns, pumps, filter presses, pug mills, forming equipment, drying ovens, and an experimental kiln capable of firing ware at high temperatures of the order of cone 18, about 2,700 deg F.

3. For clay and glaze making control: equipment for specific gravity, viscosity and moisture measurements, water analysis, and pressure and temperature recording.

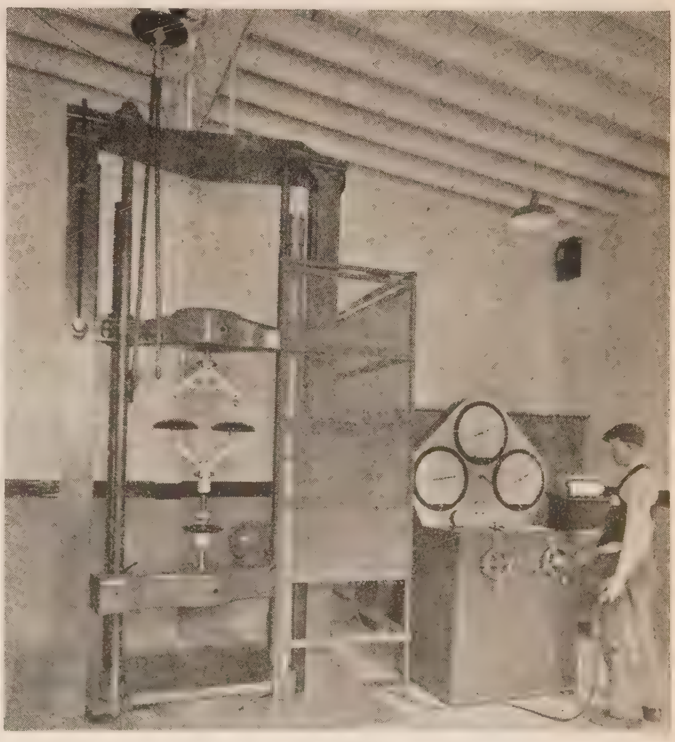

Fig. 1. Tension and compression testing machine for suspension type insulators

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 3, 1934; released for publication April 25, 1934. *Not published in pamphlet form.*

Chemical Laboratory

1. For analysis of material: chemicals and apparatus suitable for water, non-metallic and metallic minerals, metals, oils, fats, waxes, resins and gums; and ovens and balances for checks of moisture in raw materials and material in process.

2. For testing: particle size testing machine for control of body clay and glaze ingredients, cement, plaster, sand, etc.; microscopes, low and high power, with photographic facilities; and machines for rapid preparation of samples of metals, porcelain, cement, etc.; machines for tension, compression and hardness tests of metals, cement, porcelain and organic dielectrics; viscosimeter to determine flow of oils and insulating compounds; centrifuge for physical analysis of clay; oxygen bomb for accelerated aging of materials; micrometer gage for measuring minute volume changes of cement, plaster, etc.; and equipment for corrosion and other aging tests.

Mechanical Laboratory

Equipment here should be:

1. Tension and compression testing machine of about 100,000 lb capacity. If this machine is not equipped for cantilever and true torsion testing, there should be additional equipment capable of testing individual units in cantilever up to 20,000 lb, and in stacks as high as 10 or 12 ft, and in torsion up to 150,000 in. lb. All of these should be equipped with recording apparatus. A typical tension and compression machine is illustrated in Fig. 1 and a suitable cantilever and torsion machine in Fig. 2.

2. Porosity testing machine, with pressure capacity of 5,000 lb per sq in.

3. Hot and cold water tanks for thermal tests, preferably steam heated and refrigerator cooled, and capable of covering standard specification ranges. In Fig. 3 is shown one efficient form which facilitates easy and rapid handling of the insulators being tested.

4. Combined tension and thermal testing apparatus.

5. Outdoor time loading test racks. A set of outdoor racks with capacities for numerous experimental units is illustrated by Fig. 4.

Electrical Laboratory

1. Impulse generating, measuring, and recording apparatus: voltage range from 20 to 3,000 kv; high current surge capacity of order of 100,000 amp at from 100 to 150 kv with 40-μsec wave; wave length control from 0.5 μsec to 100 μsec; operating speed of at least one measured and recorded flashover per minute; high voltage potentiometers and sphere gaps capable of measuring accurately all wave crests in the voltage range.

2. Normal frequency generating, measuring, and recording apparatus: voltage range to 1,500 kv to ground; high voltage wave shape sufficiently close to sinusoidal to allow accurate calibration; high voltage potentiometers and sphere gaps capable of measuring accurately high voltage values in the range.

3. High frequency testing apparatus: oscillator equipment with voltage range to 750 kv for special insulation studies; sustained high frequency equipment for radio insulation studies.

4. Corona testing apparatus: dark room facilities, with voltage sources to 500 kv.

5. Radio interference testing apparatus: radio-interference-proof room with voltage sources to 500 kv; radio interference measuring equipment capable of making studies according to present generally accepted practices.

6. Atmospheric contamination study apparatus: suitable chamber or room for duplicating fog, dust, smoke, and other special atmospheric conditions encountered in service, with voltage sources to 300 kv; facilities for observing discharges, and measuring and recording currents and voltages associated with such discharges occurring under conditions obtained.

7. High current testing apparatus: current generating capacity up to 10,000 amp at 25 and 60 cycles, and facilities for measuring and recording same.

8. Phase angle, power factor, and similar testing apparatus: suitable instruments for measuring accurately phase angles, transformation ratios, power factors, dielectric constants, etc., in connection with low voltage circuits of bushings, constants of insulating materials, assembled units, etc.

Illustrative of a research program using the ceramic, chemical, electrical, and mechanical laboratory facilities outlined is the following example:

On one line of suspension insulators the research program extended over a period of several years at a cost of well over \$30,000. In this program the insulators were assembled in small batches of 5 or 10 units and careful attention was given to note and record the various characteristics.

During this time 171 design variations were made and tests to destruction of 2,700 units were carefully analyzed and recorded. Of these, 1,600 were special units requiring new manufacturing equipment. By the process of elimination, a few types were selected as possessing the most desirable characteristics, and these were subject to further study and tests. In the final assemblies, great care was exercised to insure that one, and only one, feature was changed at a time, and every batch of special units was paralleled by a batch of control units of a type which shows consistent performance. The final designs were subjected to all available tests. Some batches of these units loaded to 80 per cent of their average mechanical and electrical strength values, as determined by A.I.E.E. specifications, have stood the outdoor time-load test for about 2 years without a single failure. Parallel research work to secure precise measurements of the performance of the individual parts of assembled units under different loading and temperature conditions is being continued.

In selecting designs for intensive development, the determining factor was not high combined mechanical and electrical strength. In fact, 2 designs having higher strength and requiring less manufacturing expense were discarded because the construction used in them seemed hazardous. The final choice was influenced to a very great degree by the records of previous designs which have shown successful performance in service for many years.

As an example of a similar research program on another form of insulation, the development of one group of a new type of oil-filled bushing was recently completed at a cost of well over \$25,000.

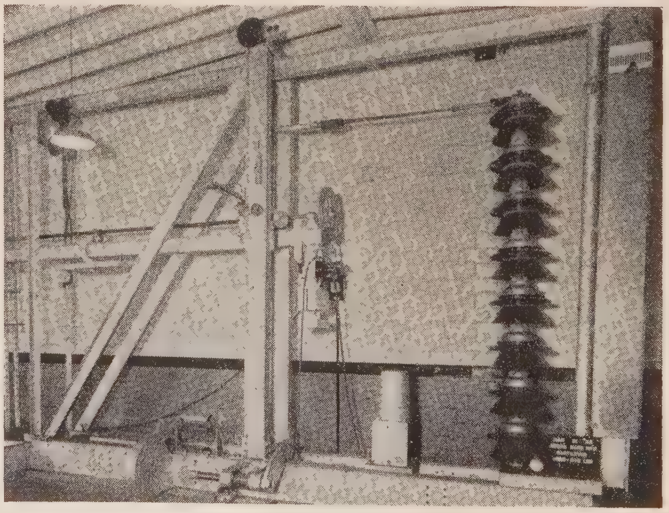

Fig. 2. Cantilever and torsion testing machine for pillar and pin type insulators

Fig. 3. Hot and cold tanks for thermal tests on insulators

Design

The basic requirements of a design are marketability for the manufacturer and economy for the user. These facts must be borne in mind by the designer. In general, designs are compromises and this is especially true with respect to insulators. Here we have 2 major requirement classifications, electrical and mechanical. As a rule these are of similar importance but, unfortunately, they dictate methods of treatment that are quite opposed to each other. Also, a design usually requires several different materials each with its own characteristics, making the derivation of formulas quite difficult or impossible. True, many phases of the design can be solved by standard or special formulas, but some of the most important features require the formulas to be modified to secure better agreement with experience. Some valuable empirical formulas are derived from both electrical and mechanical tests.

In the designing of insulators at the present time, it is probable that in most cases the general shape and type are dictated by past experience and service. Most forms derived from calculations must be modified to make them practical for manufacturing. All new designs are subjected to rigorous mechanical and electrical tests to determine their characteristics.

The relative diameters of porcelain and hardware, in so far as they effect mechanical properties, can be largely determined by formulas, and the effect of the porcelain outer diameter on flashover value can be calculated with sufficient accuracy. The relationship which holds here is that the flashover for 60 cycle or long impulse waves occurs over the shortest striking distance. For short wave or short time lag, flashover holds well to the porcelain surfaces and closely follows the leakage paths. In other words, for the first class of breakdown, insulators may be compared on the basis of their tight string or striking distances, while for the second class, which is a cascading breakdown, they may be compared by their relative total leakage distances.

The proper spacings to be used for pillar and suspension insulators from a mechanical consideration can be calculated with a fair degree of accuracy. From an electrical standpoint, insulator spacing values enter in so far as they affect the total striking and leakage distances, as noted in the previous paragraph. As a rule the diameter-spacing relationship is so arranged as to minimize the danger of cascading under average flashover conditions. Cantilever values on pillar insulators may also be satisfactorily calculated for either base or cap mounted positions, assuming that calculations or tests have previously been made to determine the strength and point of failure of a single unit.

The leakage distances and surface resistances are affected entirely by the shapes of the porcelain members. Leakage distance largely governs the flashover voltage of a unit, principally that of a cascading type such as occurs with short-time impulses. It has some bearing on the wet flashover voltages and breakdown under fog contamination conditions. Leakage distances can be raised by increasing diameters and lengths of the porcelain bodies, by adding petticoats, grooves, ribs, etc., and are comparatively easy to measure. The surface resistance of an insulator largely affects the flashover voltage and leakage current under conditions of fog, dew, surface contamination from atmospheric impurities, etc. Any increase of the total porcelain surface of an insulator from line to ground obviously raises the surface resistance to an extent depending upon the shape and location of the added surface. For example, the addition of concentric petticoats of small diameter effects much greater resistance increase than does that of larger diameters. The reason for this is that the smaller diameter petticoats add to the length of the total leakage path without contributing as great widths. A standard 10-in. diam insulator with properly arranged underneath petticoats should have a surface resistance well over twice that of a smooth disk unit with no petticoats. The theoretical surface resistance may be calculated or measured with a fair degree of accuracy, although the task is a tedious one. While this theoretical value may be some indication of the ability of the insulator to check fog flashovers, heavy leakage currents, etc., it is not an absolute criterion. This is because a calculated value assumes a uniform surface coating of moisture, dirt, carbon, etc., whereas in service this coating may vary, dependent upon the amount of protection and the degree of rain washing which the particular porcelain shape allows. Very careful study and design judgment is essential in choosing the proper porcelain shapes where leakage resistance is an important factor.

Corona on an insulator is important in so far as it

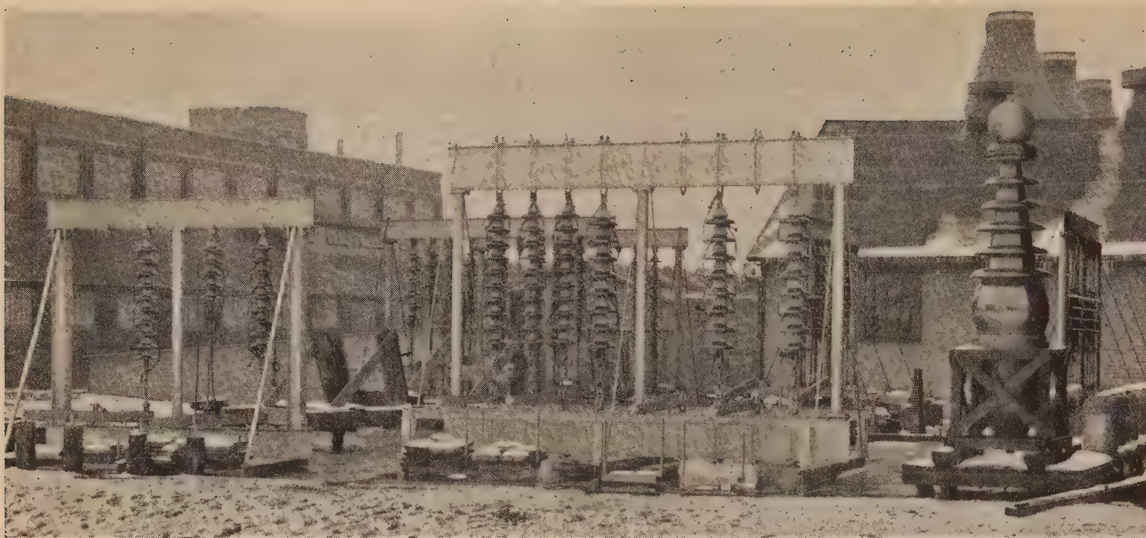

Fig. 4. Typical outdoor insulator racks for time loading tests

involves radio interference, precipitation of foreign particles on the dielectric surfaces, and possible attacks on metal parts from nitric acid formation. It may be minimized by controlling the design of both metal and porcelain members to avoid any overstress of the air at the maximum voltage at which the insulator may have to operate. Sharp metallic edges, pockets of air under metal caps or between assembled porcelain shells, etc., are typical corona origins on insulators and therefore to be avoided in design considerations. The determination of the corona and radio characteristics of an insulator must depend largely upon tests as reliable calculations are practically impossible. In addition, tests themselves are not entirely satisfactory as far as obtaining absolute design values are concerned, as there have been no standardized methods evolved as yet for measuring corona or radio characteristics. In regard to the corona tests, the principal lack is a means of determining definitely the appearance and disappearance points of the local corona discharge, since this depends upon the visual powers and position of the observer. In the case of radio interference tests the principal need is a definition of what constitutes interference in service, and how this is to be measured in the laboratory.

From the standpoint of corona and radio characteristics, however, progress in design can be effected by making comparative tests either simultaneously or successively on trial units, and determining the best from the relative performances found. So far this has served to give very satisfactory results, although the cost of comparative tests is high because of the repetition of readings and test set-ups necessary. This would be unnecessary if quantitative unit values could be obtained on individual specimens which could be depended upon for comparison with test values secured at other times.

Manufacturing

The general methods used in the manufacture of insulators are familiar to most engineers. There are, however, a number of details which will probably be of interest. Visitors to an insulator factory frequently express surprise when they see the amount of high-grade machinery and equipment used in insulator manufacturing. The nature of the materials from which insulators are made precludes the possibility of great accuracy in manufacturing. These same materials are subject to troubles which are seldom, if ever, found except in those of a fragile nature. To minimize these troubles, it is necessary to be constantly on guard and to keep machinery and equipment properly adjusted.

In the forming processes many gauges are necessary for setting forming tools and checking diameters, head thicknesses and other dimensions on green, dry and fired ware. Inspectors must be located at several positions along the manufacturing line and be provided with the necessary equipment for checking the product and detecting faults at the earliest possible moment. For control of the manufacturing process, the ceramic department should have equipment for clay conditioning and workability tests, and temperature and humidity controllers and recorders. New lots of clays, spars, and other materials should be tested, and texture and water content of the porcelain body must be watched. For kiln control it is essential to have pyrometric cones, shrinkage disks, optical pyrometers, thermocouples with recorders, draft gauges, CO_2 meters, flow meters, pressure gauges, and regulators for gas or oil firing, or fuel analysis equipment for coal firing.

In addition to the laboratories and testing equipment already mentioned, the inspection department should have proper facilities for checking quality of clay body, glaze and sand, drying, firing, assembly and curing, and for electrical and mechanical tests. Exceedingly close tolerances must be maintained wherever possible to balance up the processes which are not subject to close control. A variation in the water content of the clay body of 0.5 per cent or even less, or a slight variation in the density of the glaze, may cause much porcelain to be scrapped. A difference of 1 cone (approximately 15 deg C) in the firing range may cause rejection of over-fired ware or necessitate refiring under-fired ware. When it is realized that it is impossible to have all sections of a kiln or parts of a car at the same temperature, one

understands the importance of having adequate control methods and checks.

After the porcelain has passed through the kilns or firing process and during its progress in the assembling line, suitable equipment should be available to make the following tests and inspections: visual inspection, 60-cycle flashover and high frequency flashover part tests, and mechanical and high frequency flashover tests on assembled units. In some factories the insulators range all the way from small 1-piece telephone types to bushings composed of many parts and weighing over 5,000 lb. It is obvious that the methods of manufacturing cannot be the same in all cases, but, as an example, let us follow the suspension insulator through the assembling stage. Without going into minute details, the procedure is about as follows: A visual inspection in well lighted areas, and made by experienced men, picks out most of the defective porcelain ware. A vigorous 60-cycle flashover test will eliminate most of the remaining defective parts. The high-frequency flashover test will reveal any pieces which have defects deeply located and of such a nature that the 60-cycle test will pass them.

From the high frequency "kick test" the porcelain disks pass to the assembling area. Here the tops of the heads are dipped in paraffin to prevent any contact with cement or metal parts. The sanded surfaces or grip sections of the heads are then sprayed with a compound to give a certain amount of relief which allows for distribution of load and relief from thermal stresses. Gaskets having a low absorption factor are placed over the head. These prevent the metal caps from coming into contact with the porcelain and the lower edge of the cap from exerting a downward stress on the porcelain flange. A carefully measured amount of high-grade neat cement is placed in the cap which is then worked into position against the paper gasket.

The insulators are then placed on cars and run into the curing tanks which are heated to a predetermined temperature by live steam which deposits moisture throughout the curing process. In Fig. 5 is shown a typical battery of such curing tanks. The temperature and steam flow are controlled by thermostats, and recorded by recording thermometers. After 24 hr in the tanks the cars are removed, one at a time, for pin assembly. The first operation is to remove the paper gaskets and clean all cement out from between the lower edges of the caps and the porcelain disks. The sanded surface in the pin hole is then sprayed with a compound, after which a paper disk is forced to the bottom of the pin hole. This disk is for the purpose of providing a cushion between the head of the pin and the porcelain. A compound-coated pin is then cemented in the pin hole with a neat cement which has been carefully mixed in a small batch using definite proportions of cement and water. The pins are locked in place by stiff paper gaskets. The insulators are then returned to the curing tanks where they remain under controlled conditions of temperature and moisture for about 5 days, after which they are drawn from the tanks, cleaned and tension tested to 40 per cent of their rated load. Following the mechanical test they are subjected to a final electrical test to insure that there are no defects. The cement surfaces around the pins are then coated with wax and the insulators are crated for shipment.

Usually designs can be made to meet all specifications without working a hardship on the manufacturer. There are, however, some instances where it is very difficult to meet all of the conditions, of which one of the most notable is that of threaded porcelain pin holes. The only existing national standard covering this important feature of pin type insulators permits a greater tolerance in the manufacture of test gauges than is allowed the insulator manufacturer in the commercial production of insulators. Undoubtedly such conditions will be corrected when brought to the attention of the proper standardization committee. Both user and manufacturer have evidenced a need and desire for further general standardization, which includes defining existing design dimensions and acceptance specifications. The authors urge an early consideration of this highly desirable work, as it will be most helpful in future development.

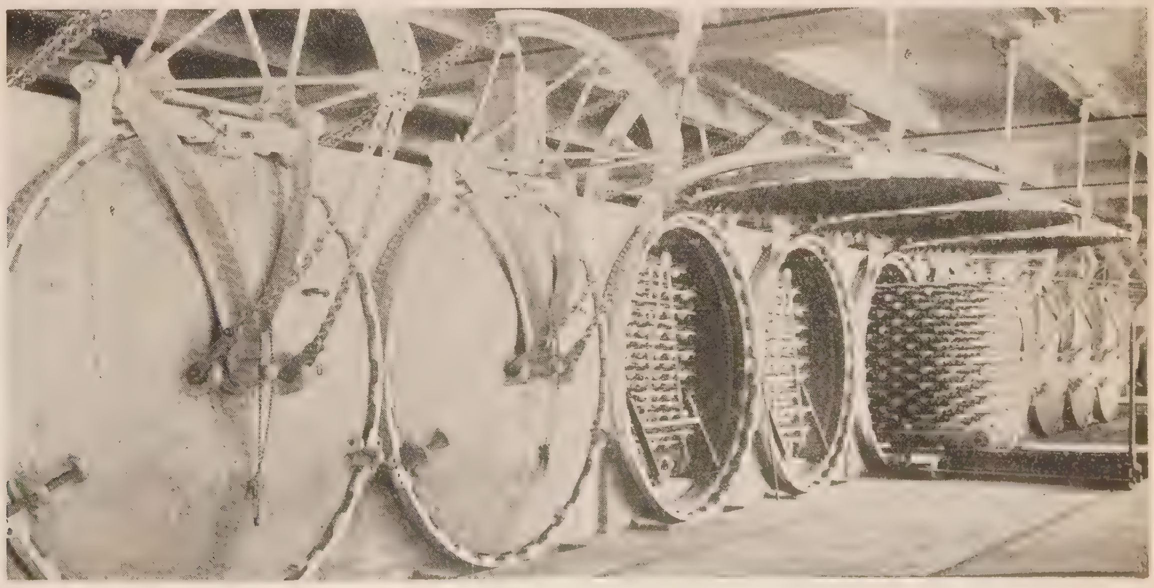

Fig. 5. Battery of insulator curing tanks

A Telemeter With Pilot Coil Transmitter

The feature of the current-type telemeter described in this paper is the pilot coil which acts as a detector of load changes.

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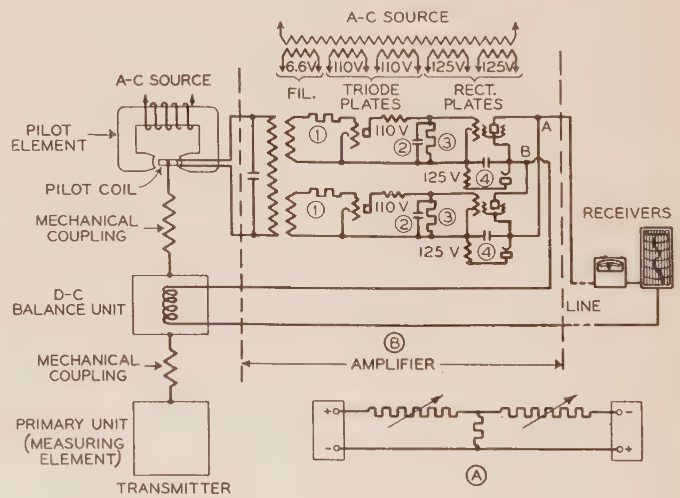
THE current-type telemeter, in which a small direct current proportional to the quantity being measured is transmitted to distant receivers, was one of the earliest and most reliable forms. It has enjoyed wide acceptance and has survived the test of successful operation. Some of the main advantages of the current system are as follows:

1. The readings are continuous.
2. The receiving instruments are simple, rugged, d-c milliammeters of either the indicating or recording type.
3. Only 2 wires are required between the transmitter and receiver.
4. The transmitted current is the same in all parts of the telemeter circuit, obviating errors present in potential schemes which are subject to leakage.
5. Telephone cable circuits are suitable for use as telemeter circuits. The telemeter current causes no interference with other circuits in the cable and the leakage resistance of the cable pair is so high as to have negligible effects on the readings.
6. Totalization of various circuits is accomplished with a high degree of accuracy by paralleling output currents.

Early forms of the current-type telemeter had the disadvantage of slow response due to designs having high inertia.[1] The continued interconnection and growth of superpower systems with the attendant interchange and sale of large blocks of power has made it necessary to telemeter quantities with high accuracy and quick response. Where 5, 10, or even 15 sec for the telemeter to travel from zero to full scale was acceptable before, conditions today require that this time be reduced to approximately 1 sec, or equal to that of corresponding indicating instruments. Furthermore, the accuracy of the telemeter must not be affected by variations in control voltage or frequency, variations in line resistance or of aging, or variation in any of the components of the apparatus.

Description of Mechanism

The new current-balance telemeter is a simple, rugged device combining the usual instrument mechanisms with conventional vacuum tube circuits and giving an accurate, quick response. The transmitter consists of 2 principal units as shown in Fig. 3. The transmitter mechanisms are mounted with their shafts in the same vertical centerline and having their moving elements mechanically coupled. The lower unit is the primary element which may be an ammeter, voltmeter, wattmeter, or any electrical or mechanical mechanism of the deflection type. The upper unit of the transmitter is a permanent-magnet moving-coil milliammeter mechanism connected to oppose the torque of the primary element. These 2 units are conventional switchboard type instrument mechanisms without pointers and with torque springs replaced by conducting strips. A small "pilot coil,"[2] which moves in an a-c electromagnetic field, is connected to the moving element system to detect any divergence of the primary element from the balance position and to adjust the current in the balancing milliammeter through an amplifier of the transformer-coupled, rectified-output type. The pilot coil acts as a detector of changes in load, obviating the use of contacts which characterized earlier forms of current telemeters. It is movable in the air gap of a stationary electromagnet having an iron core. As it is moved to either side of the null position, a voltage is induced in the coil, the magnitude of which depends upon the amount of deflection and the polarity upon the direction of deflection. The voltage output of this pilot coil is fed to an amplifier, the d-c output of which is connected in series with the balance element, the line and receiving instruments, or, in other words, feeds the telemeter circuit.



(1) 0.5 megohms (2) 0.25 μf (3) 0.25 megohms (4) 4 μf

Fig. 1. External wiring of Pilotel telemeter

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1. For numbered references see list at end of paper.

Since the torques of the balance element and the measuring element must be equal for all conditions of rest, the direct current in the balance element, line, and receivers is proportional to the quantity being metered and is thus a measure of its magnitude. This interaction may be more readily understood by noting that the system will move until the amplified pilot-coil current is just sufficient to balance the moving system.

Operation

This arrangement gives complete freedom from errors which might otherwise arise from the great changes in line resistance, wide variations in control voltage and large changes in amplifier characteristics. Any such change would tend to increase or decrease the telemeter current and thus destroy the condition of balance existing in the moving system. The resulting motion of the system would change the pilot coil output and the balance would be restored. It is apparent that the moving system of the transmitter will have a definite position for any one condition of load, control voltage, line resistance and amplifier constants, but any change in any one or more of these will cause the mechanism to move to a slightly different position to restore the balance. However, the current in the receiver is always proportional to the load except for such negligible effects as bearing friction and line leakage.

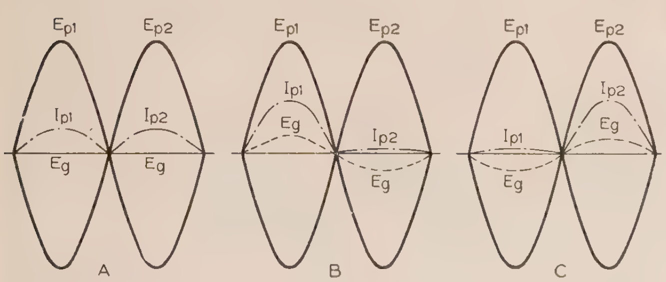

Fig. 2. Action of pilot coil under load changes

A—Pilot element at zero (no load)
B—Pilot element to right of zero
C—Pilot element to left of zero

E_p Plate voltage
I_p Plate current
E_g Grid voltage

Subnumerals 1 and 2 refer respectively to tubes Nos. 1 and 2

Action of Amplifier

The action of the amplifier may be understood by considering it as an equivalent network circuit having two separate sources of voltage. Two of the arms are variable resistances, as schematically represented by rheostats in Fig. 1A. With the separate sources connected to the network with opposite polarities as shown, the direction and magnitude of the current flowing in the fixed resistance depends upon the relative positions of the rheostats. With one rheostat set to higher resistance than the other, current will flow through the fixed resistor in one direction. Conversely, interchanging the rheostat values, the current will flow in the opposite direction.

In the actual apparatus described, the pentode tubes are analogous to the rheostats of the equivalent circuit described above. The plate currents are controlled by the grid potentials applied from the output of the pilot coil. Any change in load changes the pilot coil output and unbalances the network. See Fig. 2. The grid potentials which are controlled by the pilot output are equal for the no-load condition and hence the plate currents are equal as shown in Fig. 2A. For any condition of balance the potential difference is zero between points *A* and *B* of the bridge circuit. Any change in load changes the grid voltages. The corresponding plate currents increase and decrease accordingly, which unbalances the bridge circuit causing the potential difference between *A* and *B* to set up a proportional flow of current in the telemeter circuit. This action is reversible as will be seen by a study of Figs. 2B and 2C. Since a reversal in torque of the primary unit reverses the current in the telemeter circuit, the action is suitable for zero center scales in cases of reversals in power flow.

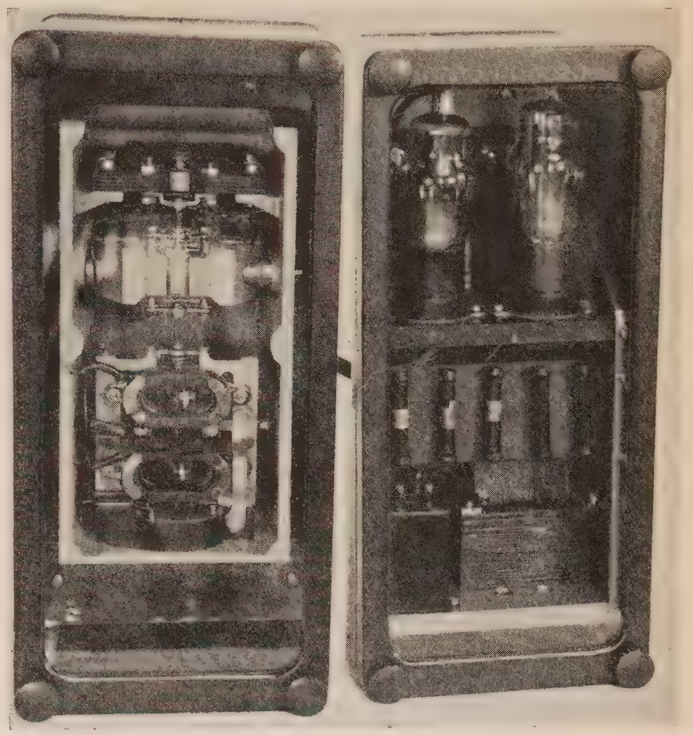

Fig. 3. Telemeter transmitter (left) and associated amplifier

Deflection

The amplification factor and the magnitude of the voltage induced in the pilot coil are so chosen that the moving system has a maximum travel of only a few degrees. Since the scale of the wattmeter

measuring element is practically uniform over this small range, totalization of the quantities of a number of circuits is accomplished with a high degree of accuracy. The responsiveness of the transmitter is higher than that of corresponding switchboard-type instruments. This is because the deflection of the moving system is only a small fraction of the deflection of the corresponding indicating instrument. When used with a Pilotel recorder receiver, the time of response of which is about 1.25 sec, the response of the telemeter system is about the same as that of an indicating wattmeter connected directly to the circuit.

Any variation in control voltage affects the output of the amplifier tubes. This tends to change the amplifier output but any such change is immediately followed by a change in the position of the moving system which compensates for such variations. Aging or change in the characteristics of the amplifier tubes is compensated for in the same manner.

Accuracy

The accuracy of the telemeter depends solely upon the calibration of the transmitter and receiver. To state this in definite figures would be to assign a probable accuracy of 1 per cent for the transmitter and for the receiving instruments. Since these units are rugged switchboard-type mechanisms, the problems of permanency of calibration and maintenance are no greater than in conventional switchboard instruments.

Actual tests have shown that sensitivity compares favorably with that of the corresponding indicating type switchboard instruments. The mechanical coupling between elements is the result of considerable development. Necessary flexibility has been obtained with negligible error caused by lag.

The d-c output derived from alternating current is filtered, but ripples or pulsates slightly. This does not affect the accuracy of the indications since the permanent magnet moving coil receiving instruments do not respond to any a-c component and read only direct current.

The use of pentode tubes, which have a high ratio of a-c impedance to d-c resistance eliminates any errors that might result from wide variation in transmission circuit characteristics.

Up to this point only primary elements which exert a torque proportional to the measured quantity have been considered. In the case of non-electrical quantities, such as pressures measured by bourdon tubes or sylphon bulbs, or positions as transmitted by position indicator motors, the measuring unit exerts a torque against the torque of the balance unit, as in the case of electrical quantities. The system described has been in operation chiefly in the laboratory, with limited field experience.

References

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Voltage Control of Vapor Rectifiers

Some of the changes to be introduced into the mathematical treatment of rectifier circuits when the firing of the anodes of a rectifier is advanced or retarded by control of the arc are described. The points considered and illustrated by theoretical curves include commutation between anodes, regulation, and wave shape of the output voltage for the more usual transformer connections, and resulting variations in functions of the transformer reactance and of the nature of the d-c load.

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DEVELOPMENT of the vapor rectifier is of comparatively recent date, the first scientific study of the vapor arc dating back only a little over 40 years[1] and the initial stage of Cooper-Hewitt's work on mercury cathode rectifiers only 33 years.[2] The expansion of the mercury cathode rectifier, which is at present the most important with respect both to size of units and to total capacity installed, was, however, very limited in extent until the advent of a steel-clad rectifier capable of successfully meeting the operating requirements of large power converting apparatus.[3] Although Schaefer's rectifier was far from having the degree of perfection now expected of modern units, it provided a starting point for the development of reliable and efficient units of large capacity. This development has resulted in an amazing expansion of the use of rectifiers for electric traction, electrolysis, lighting, communication, and other uses, which bids fair to continue at an increasing rate when the demand for power equipment returns to its normal level.

In most rectifiers now in service, the arc is entirely uncontrolled, the operation of the rectifier resting on the valve action of the anodes, i. e., their property of receiving but of not emitting electrons, and on the characteristics of the circuits associated with it. In general, a rectifier may be considered as a synchronous switch which automatically transmits to

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1. For numbered references see bibliography at end of paper.

the d-c line the voltage of whichever a-c phase has the highest momentary voltage, the different phases of the a-c line being used in rotation. Such an uncontrolled switch is incapable of any regulating action on the voltage of the d-c line, and the voltage is then regulated by tap changing, or by means of induction regulators, d-c boosters, saturated reactors, or the like.

Principle of the Arc Control

The desirability of obtaining voltage regulation or current regulation without the use of additional power equipment was felt as early as 1903 by P. H. Thomas,[4] who realized that the problem could be solved by controlling the arc. A sheet of the Thomas patent is reproduced in Fig. 1, in which the diagram (marked Fig. 1) shows the connections for a single-phase 3-wire system, and the curve (marked Fig. 4) illustrates the regulation obtainable with a 3- to 6-phase system shown in another figure of the patent.

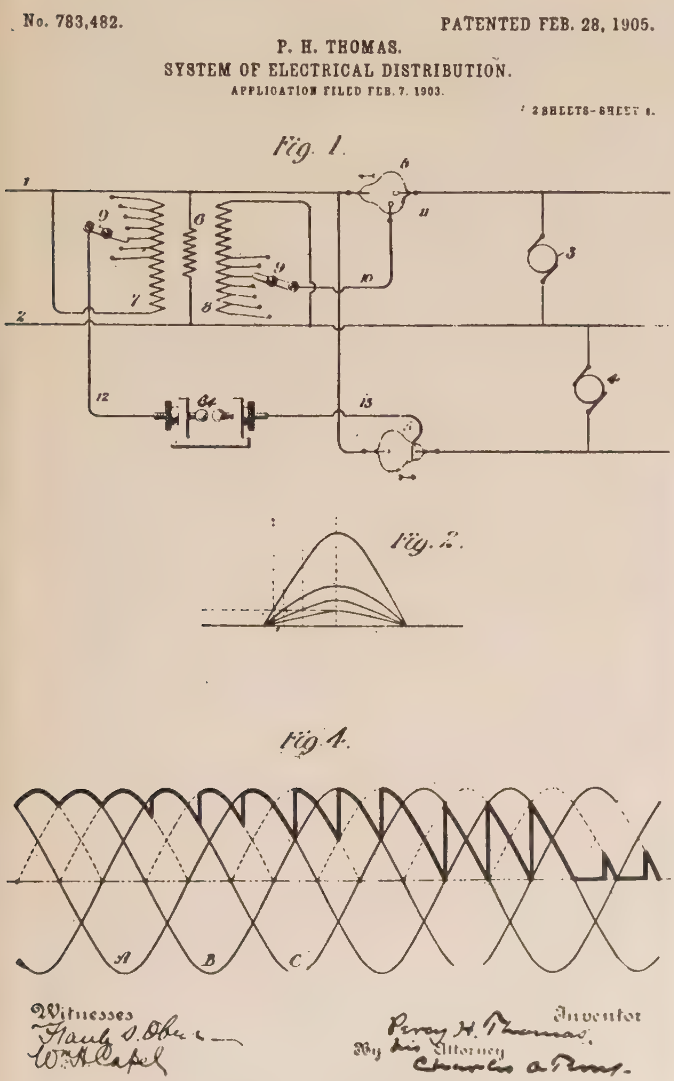


Fig. 1. Early patent for single-phase 3-wire rectifier, with voltage control by starting electrodes, and voltage curve of a similar 6-phase rectifier

The rectifier of Thomas consisted of a group of glass bulbs each having an anode and a cathode, in which the arc had to be reignited once during every cycle. This ignition was obtained by impressing a sufficiently high voltage between the cathode and an auxiliary electrode to break down the space adjacent to the cathode. This electrode may be an internal electrode *11* or an external electrode or starting band *5;* when the latter is used the electrostatic field reaches the space adjacent to the cathode through the glass wall of the bulb. The transfer of the arc from one anode to another is then always dependent upon the production of the ignition impulse and may be retarded at will during the positive half cycle of the anode voltage to impress, on the d-c line, either the peaks of the voltage waves of the successive anodes, or portions of waves of lesser magnitude. This permits regulation of the output voltage from its unregulated value down to zero.

The method of control remains essentially the same when the arc is controlled by means other than those utilized by Thomas, such as starting electrodes immersed in the mercury and electrostatic grids. The latter are now in successful commercial operation in steel-clad rectifiers of the type having several anodes and a continuously excited cathode, but are perhaps better known for their application to the control of glass rectifiers with thermionic cathodes. The grids do not call for material changes in the design of the rectifiers as may be seen from Fig. 2, which shows a 5,000-amp 625-volt rectifier provided with grid control supplying a traction load. The voltage can be regulated manually or automatically

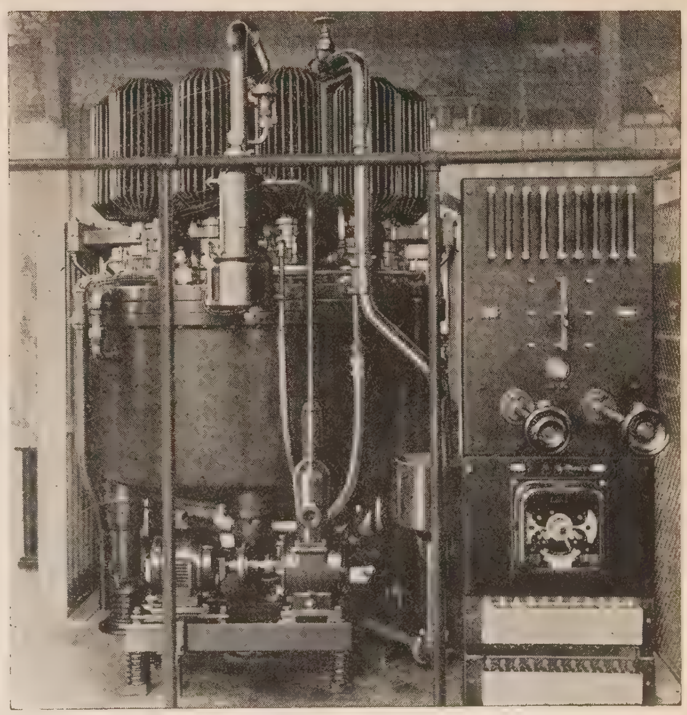


Fig. 2. 5,000-amp 625-volt mercury arc rectifier, with voltage control by grids, supplying a traction load

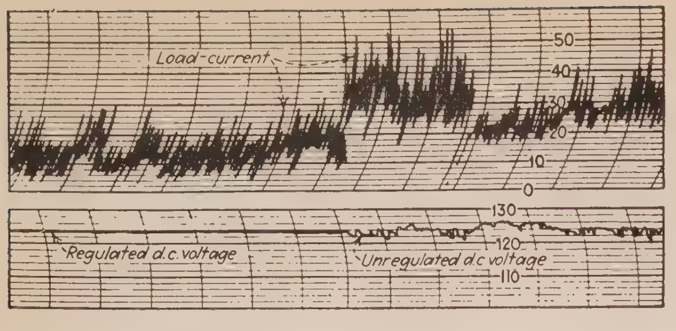


Fig. 3. Voltage and current charts of the rectifier of Fig. 2

to give to the machine a flat or a sloping characteristic. In Fig. 3 are illustrated portions of a voltage graph and of the corresponding current graph of this rectifier, clearly indicating the effectiveness of the grids in spite of constant fluctuations of the load.

The essential characteristics of the grid controlled rectifier will necessarily be deduced from the characteristics of the uncontrolled rectifier, which have been extensively considered in the literature.[5]

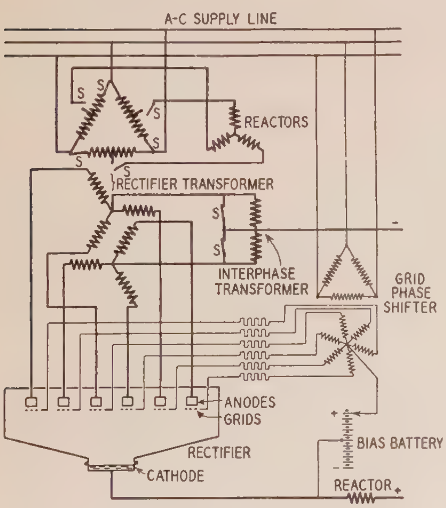


Fig. 4. Typical diagram of connections of grid controlled rectifier with or without interphase transformer

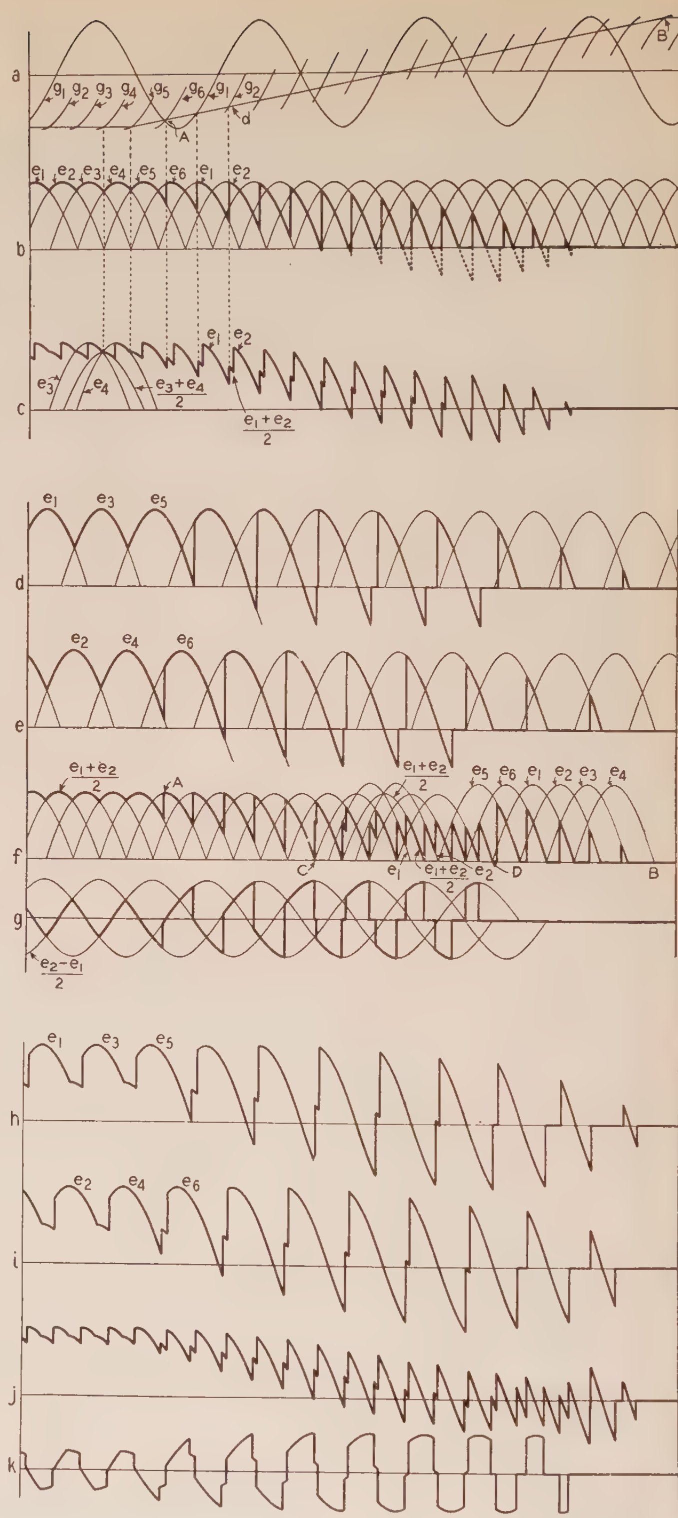


Fig. 5. Diagrams of the rectifier output voltages obtained by varying the grid voltages

a—Grid voltage: g_1 to g_6 = alternating components
d = common continuous component
b—No-load and low-load voltage: diametrical connection, solid line; voltage with resistance load, dotted lines: changes in the voltage curve with inductive load
e_1 to e_6 = anode voltage
c—Voltage on inductive load; diametrical connection; rectifier transformer working reactance 5 per cent
d to g—Diagrams for interphase transformer connection at transition resistance load
h to k—Diagrams for interphase transformer connection; transformer working reactance 12.25 per cent
d and h—Output voltage of anodes 1, 3, and 5
e and i—Output voltage of anodes 2, 4, and 6
f and j—Output voltage of the rectifier
g and k—Voltage of 1 interphase transformer coil

Connection of the Rectifier and Grids

In the following treatment only operating conditions adapted to comparatively simple computation are considered, and such approximations are made as are consistent with engineering accuracy, or as can be corrected for. Most computations relate to the general case of a p-phase rectifier, and the corresponding curves are generally drawn for the case of a 6-phase rectifier operating in one of 2 different connections obtained as shown in Fig. 4. The switches s in this figure being in the position shown, the rectifier transformer has its 3-phase primary winding connected in delta and its 6-phase secondary winding connected diametrically in star. This connection lends itself to a simple analysis of the operation of the rectifier. When all the switches s are reversed, the secondary winding is divided into

2 3-phase systems connected by an interphase transformer, and the primary winding is connected in star, each phase thereby being given a 30 deg lag. The switches are arranged also to reduce the primary turns by 50 per cent and to insert suitable reactors in each phase, so that changeover raises the secondary voltage in the ratio of 2 to $\sqrt{3}$ and increases the phase reactance in the ratio of 2.45 to 1. The rectifier, at least when operating without grids, then has the same d-c voltage and the same regulation with either connection, and the study of the interphase transformer connection, which is by far the more important of the 2, becomes easier to comprehend by a comparison with the diametrical connection.

Grids may be energized in numerous ways; in Fig. 4 they receive 6-phase alternating voltages from the line through a phase shifter, all grids receiving, in addition, a common positive or negative continuous voltage from a battery connected between the cathode and the secondary neutral point of the phase shifter. To illustrate the action of the grids with the transformer in diametrical connection, the grid voltages are assumed to lag 135 deg behind the corresponding anode voltages, and the continuous grid voltage is varied from a maximum positive value to a maximum negative value for regulating the output voltage from its maximum value to zero; any intermediate degree of regulation may then be obtained by adjusting the grid voltage to an intermediate value.

Table I—Symbols Used in Following Text

e	instantaneous secondary phase voltage
E	rms secondary phase voltage
e'_d	instantaneous regulated continuous voltage
E_{do}	average unregulated no-load continuous voltage
E'_{do}	average regulated no-load continuous voltage
E''_{do}	rms regulated no-load continuous voltage
E_d	average unregulated continuous voltage under load
E'_d	average regulated continuous voltage under load
E_{dt}	average continuous transition voltage
E'_t	rms voltage of interphase transformer coil
d	continuous grid voltage component
g	alternating grid voltage component
i	instantaneous anode current
I	continuous current
I_{dt}	transition load
K	coefficient
L	phase inductance
p	number of secondary phases
R	phase resistance
S	shaded area in Fig. 8
u	angle of overlap
x	ωt
x_o	angle of delay
y	angle of delay x_o plus angle of overlap u
X	phase reactance
X_w	phase working reactance
A_{pn}	coefficient of sine component, nth harmonic in output voltage of p-phase rectifier
B_{pn}	coefficient of cosine component, nth harmonic in output voltage of p-phase rectifier
H_{pn}	rms value, nth harmonic in output voltage of p-phase rectifier
TIF	telephone interference factor
W_n	weighting factor for the nth harmonic

No-Load Voltage With Diametrical Connection

In Fig. 5a sine curves g_1 to g_6 represent the grid alternating voltages. To release the current through its anode, each grid must be at a voltage more positive than a predetermined or critical voltage which is assumed to be the cathode voltage. This assumption is sufficiently accurate for the usual steel-clad rectifiers in which the grid alternating voltages may range from 100 to 200 volts rms while the critical voltage is within a few volts of the cathode voltage. In the figure the grid continuous voltage is represented with reversed polarity; each grid then becomes positive and releases the anode current when the grid alternating voltage curve passes from the negative to the positive side of the line representing the grid continuous voltage. Up to point A these intersections occur at the times of intersection of the anode voltages, represented by curves e_1 to e_6 in Fig. 5b. The no-load output voltage, drawn in heavy line in Fig. 5b, then consists of the peaks of the anode voltages, as in the absence of grids. The continuous voltage obtained from the anode voltage curves under different operating conditions is what may be called the gross continuous voltage; it includes the net continuous terminal voltage as actually measured at the terminals plus the arc drop in the rectifier, and also, when the rectifier is loaded, the resistance drop in the transformer. The net voltage may then be easily computed from the gross voltage; at the usual operating voltages of 600 or more the curves of the 2 voltages remain closely parallel and need not both be considered.

During interval AB the grid continuous voltage component is gradually reduced and then reversed; the grids release the anode currents at increasingly lagging points of the cycle, and the output voltage of the rectifier gradually decreases to zero.

At no load or at low resistive loads the current can flow only when the anode voltages are positive, so that the firing periods of the anodes are shortened, the flow of current being discontinuous when the firing of the anodes is delayed to a large degree.

Computation of the no-load output voltage will be considered with reference to Fig. 6, in which curves e_1 and e_2 represent the voltages of adjacent anodes of a p-phase rectifier, differing by an angle

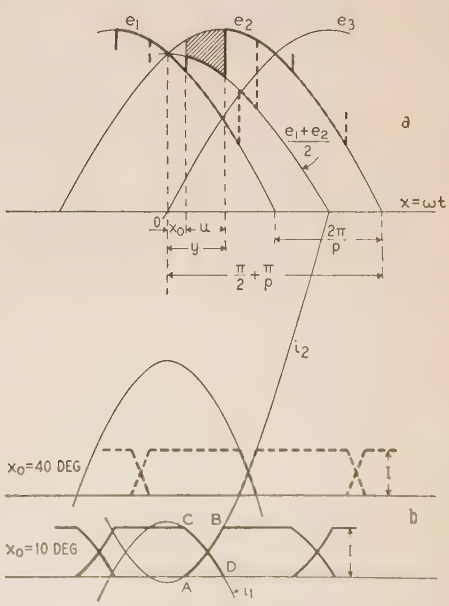


Fig. 6. Commutation of the anode currents; diametrical connection

$2/\pi p$. Taking the intersection of these curves as the origin of abscissas, the equations of the two voltages are:

$$e_1 = E\sqrt{2}\cos[x + (\pi/p)] \tag{1}$$

$$e_2 = E\sqrt{2}\cos[x - (\pi/p)] \tag{2}$$

The period of current flow of each anode extends over an angle $2\pi/p$, the flow of current in anode 2 beginning at the origin of abscissas if the rectifier is not regulated. If all the anode currents are delayed by an angle of delay x_o the firing periods of each anode will remain of normal length, finishing not later than the end of the positive half cycle, if, considering curve e_2, for example,

$$x_o + (2\pi/p) < (\pi/2) + (\pi/p)$$

or $\quad x_o < (\pi/2) - (\pi/p)$

The average gross no-load continuous voltage E'_{do} is equal to the average voltage of anode 2 during its firing period and is then

$$E'_{do} = \frac{1}{\frac{2\pi}{p}} \int_{x_o}^{x_o + \frac{2\pi}{p}} E\sqrt{2}\cos\left(x - \frac{\pi}{p}\right) dx$$

and, by integration,

$$E'_{do} = \frac{E\sqrt{2}\sin\frac{\pi}{p}}{\frac{\pi}{p}} \cos x_o \tag{3}$$

Introducing the no-load voltage E_{do} of the unregulated rectifier of value[6] $E\sqrt{2}\sin(\pi/p)/(\pi/p)$ as the unit of voltages,

$$\frac{E'_{do}}{E_{do}} = \cos x_o \tag{4}$$

showing that the no-load regulated voltage varies with the cosine of the angle of delay regardless of the number of phases of the rectifier. Equation 4 is represented by curve ABC in Fig. 7. When $(\pi/2) - (\pi/p) < x_o < (\pi/2) + (\pi/p)$ the anode firing periods are no longer consecutive and of length $2\pi/p$; integration extends only from x_o to the end of the positive anode half-cycle at angle $(\pi/2) + (\pi/p)$

and

$$E'_{do} = \frac{1}{\frac{2\pi}{p}} \int_{x_o}^{\frac{\pi}{2} + \frac{\pi}{p}} E\sqrt{2}\cos\left(x - \frac{\pi}{p}\right) dx$$

hence

$$E'_{do} = \frac{E\sqrt{2}}{\frac{2\pi}{p}} \left[1 - \sin\left(x_o - \frac{\pi}{p}\right)\right]$$

or

$$\frac{E'_{do}}{E_{do}} = \frac{1 - \sin\left(x_o - \frac{\pi}{p}\right)}{2\sin\frac{\pi}{p}} \tag{5}$$

For a 6-phase rectifier the transition between equations 4 and 5 occurs at 60 deg delay, equation 5 then being represented by curve BD in Fig. 7. Curve ABD in Fig. 7 then illustrates the gradual decrease of the voltage during interval AB in Fig. 5b.

Voltage at Low Inductive Loads

Curve ABD is also valid for pure resistance loads too low to cause an appreciable overlapping of the successive anode currents. In general, however, rectifier d-c circuits are highly inductive. For example, the inductance of ramified 600-volt railway systems averages 1 mh measured at the substation,[7] and in addition, a reactor of from 0.2 to 1 mh is frequently inserted in the d-c line to limit the current in shunt filters used for reducing the output voltage ripple. In a 6-phase rectifier supplied from a 60-cycle line the fundamental frequency of the voltage ripple is 360 cycles, at which frequency a 1-mh reactor constitutes a reactance of 2.26 ohms. In comparison, the load resistance of a 3,600-kv, 600-volt rectifier operating at 10 per cent load, which amounts to 1 ohm, is relatively small. For a first approximation, the load reactance may be considered as so large that the flow of current is sustained during all negative portions of the anode voltages, provided the average voltage remains at all positive. When the average voltage reaches zero to become negative, x_o then being equal to $\pi/2$, the anode currents are no longer consecutive and each anode fires under a voltage of zero average value, the load resistance then being zero. The continuous voltage under this inductive resistance low-load condition differs from the voltage represented by the heavy line in Fig. 5b by the addition of the dotted portions. The average value of the voltage then continues to be represented by formula 4 and follows curve ABC in Fig. 7 to point C, being zero from point C to point D.

If the load inductance is of moderate value the average voltage will follow curve ABC up to some point between B and C, and from this point will rejoin point D. In addition, the physical phenomena

ABD—Average voltage at low resistance load; diametrical connection
ABCD—Average voltage at low inductive load; diametrical connection
HKD—Rms voltage at low resistance load; diametrical connection
HKLD—Rms voltage at low inductive load; diametrical connection
ABEFG—Average voltage at resistance transition load; interphase transformer connection
ABCG—Average voltage at inductive transition load

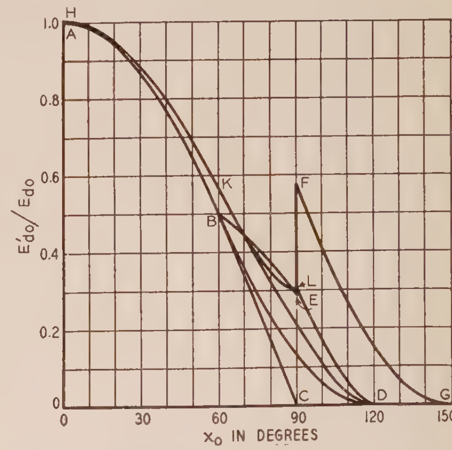


Fig. 7. Variation of the output voltage of 6-phase rectifiers as a function of the angle of delay

of the rectifier being less simple than is assumed here, the experimental values of the voltage may be appreciably lower than those in Fig. 7.[12]

In measuring the average voltage a d'Arsonval voltmeter should be used; a dynamometer voltmeter, however, should be used when the rms value of the voltage is desired. For the load conditions and for the values of x_o at which the average voltage is represented by equation 4, the rms voltage E''_{do} is expressed by

$$E''_{do} = \sqrt{\frac{1}{\frac{2\pi}{p}} \int_{x_o}^{x_o + \frac{2\pi}{p}} \left[E\sqrt{2}\cos\left(x - \frac{\pi}{p}\right)\right]^2 dx}$$

and, by integration,

$$E''_{do} = E\sqrt{1 + \frac{\sin\frac{2\pi}{p}}{\frac{2\pi}{p}}\cos 2x_o} \qquad (6)$$

The rms value of the voltage of which equation 5 gives the average value is obtained in a similar manner:

$$E''_{do} = \sqrt{\frac{1}{\frac{2\pi}{p}} \int_{x_o}^{\frac{\pi}{2} + \frac{\pi}{p}} \left[E\sqrt{2}\cos\left(x - \frac{\pi}{p}\right)\right]^2 dx}$$

hence

$$E''_{do} = E\sqrt{\frac{p}{\pi}}\sqrt{\frac{\pi}{4} + \frac{\pi}{2p} - \frac{x_o}{2} - \frac{1}{4}\sin 2\left(x_o - \frac{\pi}{p}\right)} \qquad (7)$$

On inductive short circuits, when $x_o > \pi/2$, the average voltage is zero, but the rms voltage has a value

$$E''_{do} = \sqrt{\frac{1}{\frac{2\pi}{p}} \int_{x_o}^{\pi + \frac{2\pi}{p} - x_o} \left[E\sqrt{2}\cos\left(x - \frac{\pi}{p}\right)\right]^2 dx}$$

hence

$$E''_{do} = E\sqrt{\frac{p}{\pi}}\sqrt{\frac{\pi}{2} + \frac{\pi}{p} - x_o - \frac{1}{2}\sin 2\left(x_o - \frac{\pi}{p}\right)} \qquad (8)$$

The values of E''_{do} given by formulas 6, 7, and 8, and divided by E_{do}, are plotted as curves *HKL*, *KD*, and *LD*, respectively, corresponding to curves *ABC*, *BD*, and line *CD* of the average voltage. The no load rms voltage then follows curve *HKD*, and the low inductive load voltage curve *HKLD*. Actually, with a load inductance of moderate value, the voltage will rejoin point *D* from a point intermediate between *K* and *L*.

When the rectifier load consists only of a voltmeter of comparatively high resistance and of a comparatively large condenser, the condenser being directly connected across the d-c line or being part of a shunt filter, the condenser is charged at the peak value of the output voltage and remains charged at this value, except that it discharges to some extent through the meter between successive voltage peaks. The voltmeter then reads slightly less than $E\sqrt{2}$ if $x_o < \pi/p$, and reads slightly less than $E\sqrt{2}\cos[x_o - (\pi/p)]$ for greater values of x_o up to $(\pi/2) + (\pi/p)$.

Voltage Under Load

Operation of a *p*-phase rectifier will next be considered assuming that it carries a d-c load *I*, and that the load reactance is large enough to effectively suppress the ripple of the load current. Each transformer phase is affected by an inductance *L* and a resistance *R*, both referred to the secondary side and including the inductance and resistance of the a-c supply line from the generator to the rectifier. Again, considering the operation of anodes 1 and 2, receiving voltages e_1 and e_2, upon release of the arc at anode 2 the current in anode 1 gradually decays during an interval *u* while the current in anode 2 rises to its full value *I*. This transient condition is caused by the phase inductances, phases 1 and 2 momentarily forming a circuit closed by the arc, to which Kirchhoff's second law may be applied:

$$e_1 - Ri_1 - L\,di_1/dt - (e_2 - Ri_2 - L\,di_2/dt) = 0 \qquad (9)$$

Solving equations 1, 2, and 9 simultaneously, the formula for i_2 during the commutating period is obtained:

$$i_2 = \frac{E\sqrt{2}\sin\frac{\pi}{p}}{\sqrt{R^2+X^2}}\left[\sin(x-\varphi) - \epsilon^{\frac{R}{X}(x_o - x)}\sin(x_o - \varphi)\right] + \frac{I}{2}\left(1 - \epsilon^{\frac{R}{X}(x_o - x)}\right) \qquad (10)$$

where $\varphi = \tan^{-1}(X/R)$ and $X = \omega L$. Once i_2 is known, i_1 is obtained from the relation

$$i_1 + i_2 = I \qquad (11)$$

Formula 10 shows that i_2 consists of a steady state sinusoidal component superimposed on a steady state d-c component and 2 logarithmic transient components. Fortunately, the commutation between anodes occupies only a small part of the cycle, usually less than 30 deg, and the ratio X/R is generally large, of the order of 3, so that no appreciable error is made in neglecting *R* and in therefore assuming the transient components of i_2 to be constant. Under these assumptions

$$i_2 = \frac{E\sqrt{2}\sin\frac{\pi}{p}}{X}(\cos x_o - \cos x) \qquad (12)$$

and hence from equation 11

$$i_1 = I - \frac{E\sqrt{2}\sin\frac{\pi}{p}}{X}(\cos x_o - \cos x) \qquad (13)$$

In Fig. 6b are shown in full lines the wave shape of i_1 and i_2 as given by formulas 12 and 13 for an angle of delay of 10 deg. Only portion *AB* of curve i_2 is useful, i_2 being equal to *I* from point *B* on; i_1 varies from *I* to zero as shown by portion *CD* of curve i_1.

During interval *AD*, the gross continuous voltage of anodes 1 and 2 firing in parallel is:

$$e'_d = e_2 - L\,di_2/dt$$

This formula, combined with equation 9 in which, in view of equation 11, $di_1 = -di_2$, gives

$$E'_d = \frac{e_1 + e_2}{2} \qquad (14)$$

During the periods of overlap, anodes 1 and 2 thus operate at the average of their phase voltages, giving to the continuous voltage curve the aspect indicated by the heavy line in Fig. 6a.

Angle of Overlap

This same figure also shows in dotted lines the current and voltage curves for $x_o = 40$ deg, the axis of the currents being displaced by the proper amount to permit using again the curve of i_2 drawn previously and to illustrate the gradual decrease of the angle of overlap u for increasing values of x_o. It is, however, more convenient to consider, instead of the angle of overlap, the angle $y = x_o + u$, representing the delay in the full voltage operation of the anode, and which may be considered as a generalization of the angle u. Substituting the value y for x in formula 12 gives:

$$\cos x_o - \cos y = \frac{IX}{E\sqrt{2}\sin\frac{\pi}{p}} \tag{15}$$

For computing y it is convenient to utilize a quantity X_w, which will be referred to as "working reactance," which, when referred to the primary side and measured with the d-c line short circuited and carrying the current I, is related to I, X, and E by the formula

$$X_w = 100\frac{I_pX_p}{E_p} \tag{16}$$

Therefore X_w is simply the familiar percentage reactance X per cent[8] multiplied by the ratio of the

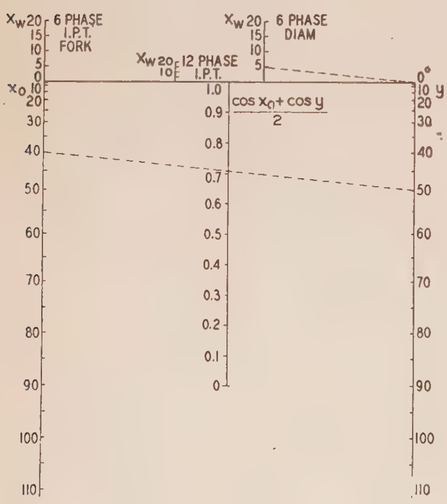


Fig. 8. Chart for computing angle of overlap and average continuous voltage

load I being considered to the full load, and which becomes equal to X per cent at full load. The relation between E_p, I_p, X_p, and E, I, and X differs with the transformer connection; and for any particular connection formula 15 may be written

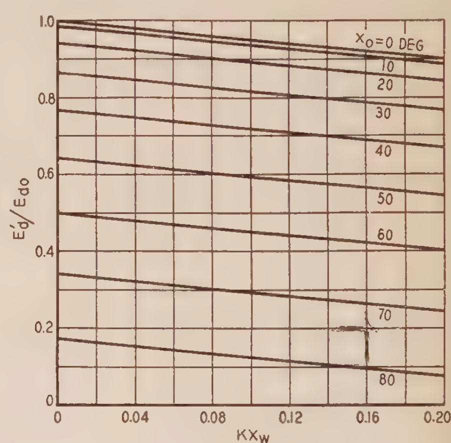
$$\cos x_o - \cos y = KX_w \tag{17}$$

where K is the familiar coefficient of the formula $\cos u = 1 - KX$ relative to uncontrolled rectifiers[8] and corresponding to $x_o = 0$ in formula 17. In general, $E_p = E$ and $X_p = X$, so that

$$K = \frac{I}{I_p}\,\frac{1}{100\sqrt{2}\sin\frac{\pi}{p}} \tag{18}$$

The value of K is 0.0245 for the 6-phase diametrical connection, 0.01 for the 6-phase fork or interphase transformer connection and 0.0516 for the 12-phase interphase transformer connection. Figure 8 is a chart of formula 17. Below the axis of abscissas 2 parallel vertical lines carry linear scales of $\cos x_o$ and $\cos y$, respectively, but are graduated in values of x_o and y. Above the axis other vertical lines carry scales of X_w for the 4 transformer connections mentioned above. The scales are so arranged that when a line is drawn between the point marked with the value of X_w considered and a fixed point on the axis all pairs of values of x_o and y are joined by lines parallel to this line. For example, if $X_w = 5$ per cent (diametrical connection)

Fig. 9. Regulation curves for different values of the angle of delay



and $x_o = 40$ deg, y will be 50 deg, and, by difference, $u = 10$ deg.

To obtain the voltage under load in Fig. 5, the values of x_o for each cycle are read on Fig. 5a; y or u is obtained from Fig. 8, and a period of overlap is added in each cycle of Fig. 5b as indicated in Fig. 6, thus obtaining Fig. 5c. This figure is purely illustrative, as it is drawn under the academic assumption of an inductive load drawing a constant current regardless of the voltage. The quantity X_w is taken as 5 per cent, a representative figure for rectifiers operating at full load.

The effect of the phase reactance under load is to decrease the continuous voltage by the shaded area in Fig. 6. The value of this area is

$$S = \int_{x_o}^{y}\frac{e_2 - e_1}{2} = \int_{x_o}^{y} E\sqrt{2}\sin\frac{\pi}{p}\sin x\,dx$$
$$= E\sqrt{2}\sin\frac{\pi}{p}(\cos x_o - \cos y)$$

or, in view of formulas 17 and 18,

$$S = E\frac{I}{I_p}\frac{X_w}{100} \tag{19}$$

and is, therefore, a constant at constant current. The voltage then becomes

$$E'_d = E'_{do} - \frac{S}{\frac{2\pi}{p}} = E'_{do} - \frac{E\sqrt{2}\sin\frac{\pi}{p}}{\frac{2\pi}{p}}(\cos x_0 - \cos y) \tag{20}$$

Hence, in view of formula 4,

$$E'_d = E_{do}\cos x_o - \frac{E_{do}}{2}(\cos x_1 - \cos y) \tag{21}$$

and

$$\frac{E'_d}{E_{do}} = \frac{\cos x_o + \cos y}{2} \tag{22}$$

This value is read directly on the central vertical line in Fig. 8, and is 0.704 in the example chosen. From formulas 17, 20, and 21 also follows:

$$E'_d = E'_{do} - \frac{KX_w}{2}E_{do} \tag{23}$$

and

$$\frac{E'_d}{E_{do}} = \cos x_o - \frac{KX_w}{2} \tag{24}$$

The above relations obtain up to $x_o = \pi/2$; at greater values of x_o the anode currents are no longer consecutive, and the rectifier operates at zero average continuous voltage on an inductive short circuit. The curves of the average voltage in function of x_o at different loads are all identical to curve *ABC* in Fig. 7, but are displaced vertically below *ABC* by the amount $KX_w/2$. The curves of the voltage in function of KX_w are parallel straight lines, shown in Fig. 9. The inherent regulation is the same for any value of x_o, including the value zero obtained in the unregulated rectifier. This figure may also be provided with different scales of abscissas graduated in values of X_w for the values of K corresponding to any desired connection.

Back Emf Load and Output Voltage Harmonics

In general, the load of a rectifier, in addition to being inductive, consists for the most part of a back emf due, for instance, to traction motors or to electrolytic cells. In many instances, also, rectifiers are operated in parallel with synchronous converters or with d-c generators. In either case voltage regulation of the rectifier by grids, which increases the ripple of the rectifier output voltage, may result in the rectifier net voltage being lower than the load back emf or the voltage of the other converters. As long as the average net voltage of the rectifier remains higher than the back emf or generator voltage, and provided that the rectifier d-c feeder has considerable inductance, the anode currents remain consecutive and the rectifier output current remains continuous at the voltage obtained above for the inductive load condition. When these conditions are no longer fulfilled, however, the current consists of a succession of non-consecutive impulses, and when the rectifier peak output voltage is less than the back emf or generator voltage, the rectifier ceases operating.

The value e'_d of the regulated output voltage of a p-phase rectifier may be represented by a Fourier series similar to the series representing the unregulated voltage,[9] but in which the constant term has the new value E'_d. Thus

$$e'_d = E'_d + \Sigma A_{pn}\sin npx + \Sigma B_{pn}\cos npx \tag{25}$$

coefficients A and B being obtained by integration over a complete ripple of the output voltage:

$$A_{pn} = \frac{p}{\pi}\int_{x_o}^{x_o+\frac{2\pi}{p}} e'_d \sin npx\, dx$$

$$B_{pn} = \frac{p}{\pi}\int_{x_o}^{x_o+\frac{2\pi}{p}} e'_d \cos npx\, dx$$

For this integration e'_d may be separated into an overlap portion and a full anode voltage portion:

$$e'_d = \left[\frac{e_1+e_2}{2}\right]_{x_o}^{y} + \left[e_2\right]_{y}^{x_o+\frac{2\pi}{p}}$$

$$= \left[E\sqrt{2}\cos\frac{\pi}{p}\cos x\right]_{x_o}^{y} + \left[E\sqrt{2}\cos\left(x-\frac{\pi}{p}\right)\right]_{y}^{x_o+\frac{2\pi}{p}}$$

Hence,

$$A_{pn} = \frac{pE\sqrt{2}}{\pi}\left[\int_{x_o}^{y}\cos\frac{\pi}{p}\cos x\sin npx\, dx + \int_{y}^{x_o+\frac{2\pi}{p}}\cos\left(x-\frac{\pi}{p}\right)\sin npx\, dx\right]$$

and, by integration, and dividing by E_{do},

$$\frac{A_{pn}}{E_{do}} = \frac{1}{2}\left[\frac{\sin(np+1)y}{np+1} - \frac{\sin(np-1)y}{np-1} + \frac{\sin(np+1)x_o}{np+1} - \frac{\sin(np-1)x_o}{np-1}\right] \tag{26}$$

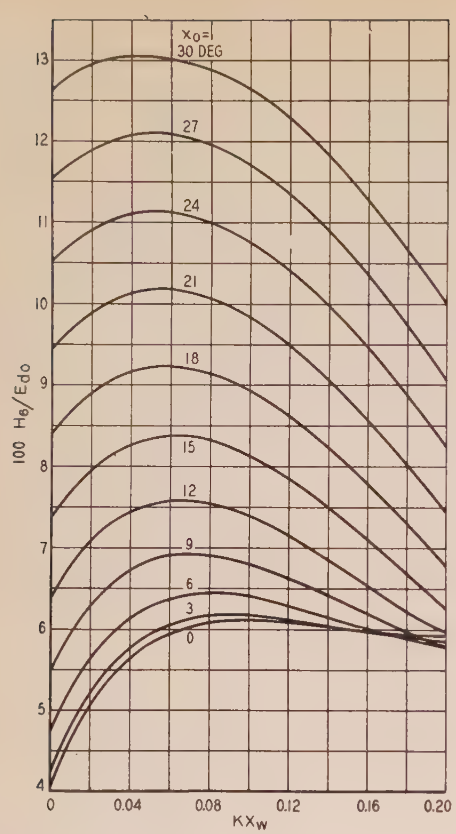
B_{pn} is obtained in a similar manner:

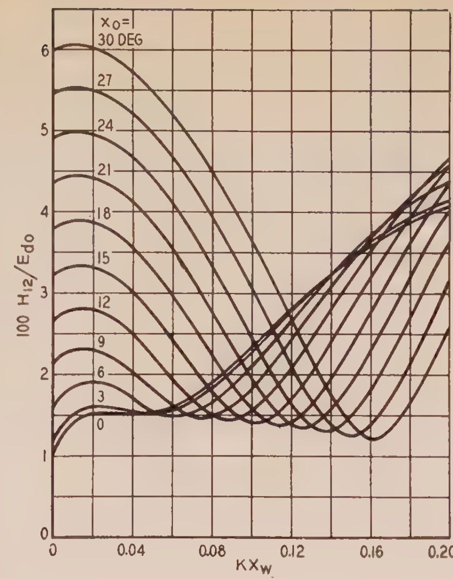
$$\frac{B_{pn}}{E_{do}} = \frac{1}{2}\left[\frac{\cos(np+1)y}{np+1} - \frac{\cos(np-1)y}{np-1} + \frac{\cos(np+1)x_o}{np+1} - \frac{\cos(np-1)x_o}{np-1}\right] \tag{27}$$

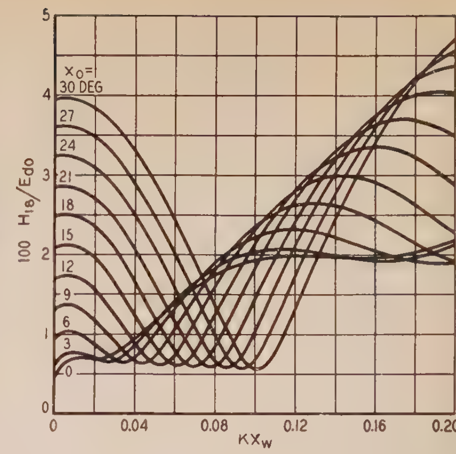
The rms value H_{pm} of the nth harmonic, expressed in per cent of the no-load unregulated voltage E_{do}, is

$$100\frac{H_{pn}}{E_{do}} = 100\sqrt{\frac{\left(\frac{A_{pn}}{E_{do}}\right)^2 + \left(\frac{B_{pn}}{E_{do}}\right)^2}{2}} \tag{28}$$

Figures 10, 11, and 12 show formula 28 plotted for the sixth, twelfth, and eighteenth harmonics, of orders 1, 2, and 3, respectively, of 6-phase rectifiers for a few values of x_o, against abscissas of KX_w. Formulas 26 and 27 contain, as variables, the product np, x_o, and y; the latter is obtained in function of x_o and KX_w from formula 17. These figures, therefore, give the values of harmonics of order n in any polyphase rectifier where pn is equal to 6, 12, and 18. In particular Fig. 11 is directly applicable to 12-phase rectifiers, in which the twelfth harmonic







Figs. 10, 11, and 12. Sixth (left), twelfth (center), and eighteenth (above) harmonic components of the output voltage

is of order 1. Theoretically the sixth and eighteenth harmonics are absent from the output voltage of 12-phase rectifiers, but unequal division of load between the 2 sets of 6 phases causes these harmonics to appear[13] and it is not improbable that, in each particular case, they vary in accordance with Figs. 10 and 12, read with larger scales of ordinates.

The different harmonics of orders n each have a phase angle equal to $\tan^{-1} B_{pn}/A_{pn}$ with respect to the origin 0 of angles in Fig. 6. When the primary voltage of the rectifier is not sinusoidal, its harmonics cause the appearance, in the output voltage, of harmonics of the same order as those due to the action of the rectifier. The harmonics from the 2 causes should be added vectorially to obtain their measurable aggregate value.

6-Phase Operation With Interphase Transformer

All the switches s in Fig. 4 being reversed, the anode voltages are retarded 30 deg and increased in the ratio of 1 to cos 60 deg; their curves e_1 to e_6 are shown in Figs. 5d and 5e, anodes 1, 3, and 5 operating as in a 3-phase rectifier, and anodes 2, 4, and 6 operating as in another 3-phase rectifier, the parallel operation of the 2 systems being insured by the interphase transformer. In Figs. 5d and 5e the heavy lines represent the output voltages of the systems when controlled by the grids, again energized as shown in Fig. 5a. These voltages are not drawn for no load operation, the interphase transformer then being inoperative, but for a low non-inductive load not less than the lowest load at which the interphase transformer operates normally, the so-called transition load.[10] The value of the transition load varies with the value x_o; it is of the order or magnitude of 2 per cent of full load for $x_o = 0$, and causes no material overlapping of the anode currents. The voltages across the 2 halves of the interphase transformer are necessarily equal so that when the interphase transformer is effective, the gross instantaneous output voltage of the rectifier is the average of the output voltages of the 2 systems, shown in Figs. 5d and 5e. This voltage is drawn in Fig. 5f, which is identical with Fig. 5b for $x_o < (\pi/2) - (\pi/p)$; its average value is given by formula 4, in which E_{do} is, however, to be replaced by the transition voltage $E_{dt} = E\sqrt{2} \sin (2\pi/p)/(2\pi/p)$. The average value of the voltage is then also represented by curve AB in Fig. 7. This operating condition obtains up to point C in Fig. 5f, at which the voltage begins presenting negative portions. Between points C and D the flow of current occurs alternately through 2 anodes and through a single anode. When the momentary voltage is positive, current is carried simultaneously by 1 anode of each system, and when it drops to zero the negative anode ceases firing and the positive anode continues alone at its own phase voltage until another anode forms a new pair with it. From the transition value of the load up, when the current is carried by a single anode, the core of the interphase transformer is highly saturated and, although the interphase transformer then operates as a reactor in the anode circuit, its effect is negligible.

This operating condition is illustrated in detail in Fig. 13, in which the origin of angles previously used in Fig. 6 is retained; the continuous voltage consists of consecutive portions of curves of e_1 and $(e_1 + e_2)/2$, represented by the formula:

$$e'_d = \left[E\sqrt{2}\cos x\right]_{\frac{\pi}{2}-\frac{\pi}{p}}^{x_o} + \left[E\sqrt{2}\cos\frac{\pi}{p}\cos\left(x-\frac{\pi}{p}\right)\right]_{x_o}^{\frac{\pi}{2}+\frac{\pi}{p}}$$

and, by integration, its average value is

$$E'_d = \frac{E\sqrt{2}}{\frac{2\pi}{p}}\left[\int_{\frac{\pi}{2}-\frac{\pi}{p}}^{x_o} \cos x \, dx + \int_{x_o}^{\frac{\pi}{2}+\frac{\pi}{p}} \cos\frac{\pi}{p}\cos\left(x-\frac{\pi}{p}\right) dx\right]$$

and

$$E'_d = \frac{E\sqrt{2}}{\frac{2\pi}{p}} \sin\frac{\pi}{p}\cos\left(x_o-\frac{\pi}{p}\right)$$

Hence, introducing E_{dt} as a unit,

$$\frac{E'_d}{E_{dt}} = \frac{\cos\left(x_o-\frac{\pi}{p}\right)}{2\cos\frac{\pi}{p}} \tag{29}$$

Formula 29 is represented by curve BE in Fig. 7, and is valid up to $x_o = \pi/2$.

When $x_0 > \pi/2$, each anode of one system becomes negative and ceases firing before the following anode of the other system is released; the 2 systems then carry current alternately in non-consecutive periods and operate as a single p-phase system. The voltage is then

$$E'_d = \frac{1}{\frac{2\pi}{p}}\int_{x_o}^{\frac{\pi}{2}+\frac{2\pi}{p}} E\sqrt{2}\cos\left(x-\frac{2\pi}{p}\right) dx$$
$$= \frac{E\sqrt{2}}{\frac{2\pi}{p}}\left[1-\sin\left(x_o-\frac{2\pi}{p}\right)\right]$$

and hence

$$\frac{E'_d}{E_{dt}} = \frac{1-\sin\left(x_o-\frac{2\pi}{p}\right)}{\sin\frac{2\pi}{p}} \tag{30}$$

Formula 30 is represented by curve FG in Fig. 7. When x_o is varied from zero to 150 deg there is, therefore, a considerable discontinuity in the continuous voltage for $x_o = 90$ deg.

The voltage across each half of the interphase transformer is equal to the difference between the ordinates of Figs. 5d and 5f or 5e and 5f, or to half of the difference between the ordinates of Figs. 5d and 5e. In a p-phase system of frequency f, this voltage is of frequency $pf/2$, but is not sinusoidal, its value following only portions of sine curves of the form $E\sqrt{2}\sin(\pi/p)\sin x$. It is represented by the heavy line in Fig. 5g and in Fig. 13.

For $x_o < (\pi/2) - (\pi/p)$ the rms value of the voltage is

$$E'_t = \sqrt{\frac{p}{2\pi}\int_{x_o}^{x_o+\frac{2\pi}{p}}\left[E\sqrt{2}\sin\frac{\pi}{p}\sin\left(x-\frac{\pi}{p}\right)\right]^2 dx}$$

which, by integration, gives the relative values of this voltage compared to the phase voltage E:

$$\frac{E'_t}{E} = \sin\frac{\pi}{p}\sqrt{1-\frac{p}{2\pi}\sin\frac{2\pi}{p}\cos 2x_o} \tag{31}$$

Formula 31 applied to the 6-phase rectifier is represented by curve AB in Fig. 14. When $(\pi/2) - (\pi/p) < x_o < \pi/2$ the operating period of frequency $pf/2$ of the interphase transformer is less than $2\pi/p$ as its action is suspended during the period of single-anode operation. The interphase transformer voltage is then

$$E'_t = \sqrt{\frac{p}{2\pi}\int_{x_o}^{\frac{\pi}{2}+\frac{\pi}{p}}\left[E\sqrt{2}\sin\frac{\pi}{p}\sin\left(x-\frac{\pi}{p}\right)\right]^2 dx}$$

hence

$$\frac{E'_t}{E} = \sin\frac{\pi}{p}\sqrt{\frac{p}{\pi}}\sqrt{\frac{\pi}{2p}+\frac{\pi}{4}-\frac{x_o}{2}+\frac{1}{4}\sin 2\left(x_o-\frac{\pi}{p}\right)} \tag{32}$$

as represented by curve BC in Fig. 14.

For $x_o > \pi/2$ the interphase transformer acts as a saturated reactor and its voltage is generally negligible.

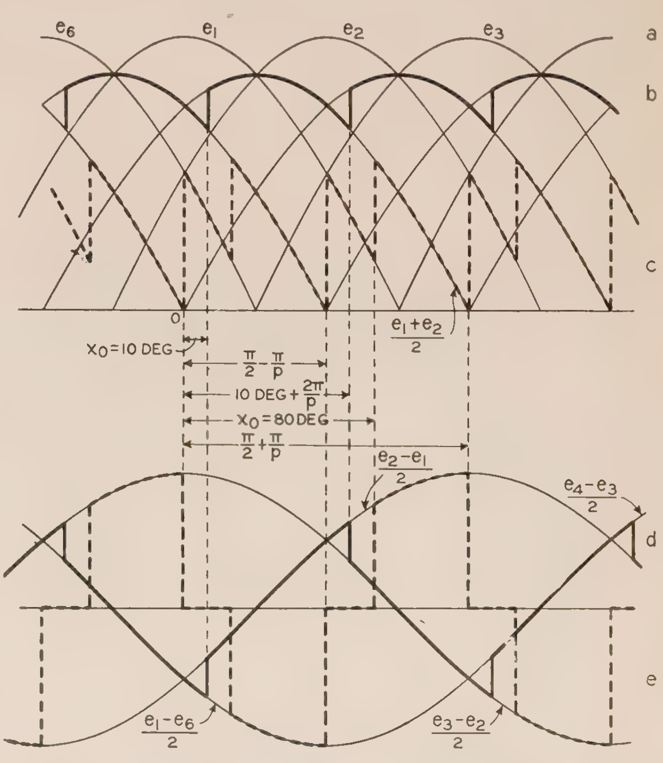


Fig. 13. Voltage output of p-phase rectifier with interphase transformer; alternate single- and 2-anode operation at resistance transition load

a—Anode voltages
b—Continous voltage, x_o — 10 deg
c—Continuous voltage, x_o — 80 deg
d—Interphase transformer coil voltage, x_o — 10 deg
e—Interphase transformer coil voltage, x_o — 80 deg

Figures 5h to 5k are the counterparts of Figs. 5d to 5g, assuming the same value of reactive load as in Fig. 5c and a working reactance of 12.25 per cent to obtain the same characteristics with both connections. Considering that at full load the working reactance of rectifier transformers is in the neigh-

borhood of 5 per cent regardless of their connections, Fig. 5c is representative of actual full-load operation, and Figs. 5h to 5k correspond to actual operation at 2.45 times full load. The load being inductive, the continuous current is maintained uninterrupted until the average continuous voltage reaches zero. Under these conditions the voltage curve in Fig. 5j is identical with the curve of Fig. 5c, and its value is given by curve ABC in Fig. 7, displaced downward by $KX_w/2$. The regulation curves for these conditions are again those of Fig. 9, except for values of load below the transition load E_{dt}. When the average value of the voltage of the rectifier, with the 2 systems operating in parallel, becomes negative, alternate 1- and 2-anode operation is established, and when the average value of voltage under these conditions becomes negative, the rectifier operates instead as a diametrical 6-phase unit with non-consecutive anode firing periods.

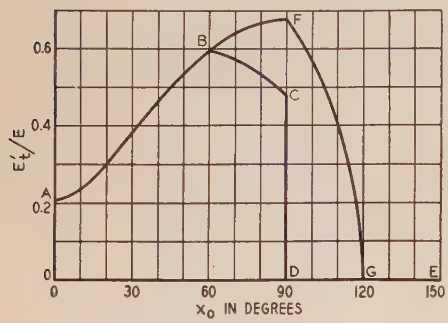


Fig. 14. Voltage (rms) of one coil of interphase transformer of a 6-phase rectifier

ABCDE—Voltage at resistance transition load

ABFGE—Voltage at inductive transition load

The interphase transformer half-voltage is shown in Fig. 5k. The operation of the interphase transformer is continuous up to $x_o = \pi/2$, so that, if the overlap is neglected, its half-voltage is represented by formula 31, giving curve ABF in Fig. 14. When $\pi/2 < x_o < (\pi/2) + (\pi/p)$

$$E'_t = \sqrt{\frac{p}{2\pi}\int_{x_o}^{\frac{2\pi}{p} + \pi - x_o} \left[E\sqrt{2}\sin\frac{\pi}{p}\sin\left(x - \frac{\pi}{p}\right)\right]^2 dx}$$

hence

$$\frac{E'_t}{E} = \sin\frac{\pi}{p}\sqrt{\frac{p}{\pi}}\sqrt{\frac{\pi}{p} + \frac{\pi}{2} - x_o + \frac{1}{2}\sin 2\left(x_o - \frac{\pi}{p}\right)} \tag{33}$$

which is represented by curve FG in Fig. 14.

For $x_o > \pi/2$ the interphase transformer is inactive and its voltage is nearly zero. Formulas 31 and 33 are accurate only if the overlap is negligible; in general, the angles of overlap are considerably smaller than those shown in Fig. 5k, and the error is not considerable. When x_o is large, the values given by the formulas are somewhat in excess, and are, therefore, safe for interphase transformer calculations. When the rectifier load includes a back emf, or if generators are connected in parallel with the rectifier, the rectifier current will remain continuous as long as the average output voltage of the rectifier is greater than the system emf. When x_o is further increased, the rectifier operates alternately on 1 and 2 anodes, and the current is still continuous if the average voltage then obtained is greater than the system emf.

As is well known, the no-load voltage of the uncontrolled rectifier with interphase transformer is materially higher than the voltage under load. This effect is present also when the voltage is regulated by grids[14] and, although the no-load regulated voltage is always lower than the no-load unregulated voltage, the voltage rise may be greater in proportion and should be guarded against. This phenomenon can be avoided to a certain extent. For example, each grid may be so controlled as never to remain positive for any material length of time. Considering the anode voltages in Fig. 13, and remembering that at no load the rectifier operates as in diametrical 6-phase connection, if $x_o < \pi/p$, and anode the 1 is carrying current, anode 2 is released when it is negative with respect to anode 1 and it does not take the arc; when anode 2 becomes more positive than anode 1 it is again blocked by its grid, and the arc can only be transferred to anode 3. Only the system of anodes 1, 3, and 5 then operates and the continuous voltage remains at its transition value for the value of x_o utilized. The system of anodes 2, 4, and 6 may also be completely blocked by making the grids negative with a load responsive relay.[15]

Limitations of Grid Control

Voltage regulation by means of grid control is of universal application, being suited equally well to glass and to steel-clad rectifiers, regardless of the nature of the load. The advantages of its use in preference to other methods of control should, however, be determined in each case, particularly with regard to efficiency and power factor.

In an uncontrolled rectifier, if the transformer magnetizing current and the anode current overlap are neglected, the power factor of the primary current differs from unity only because of the distorted shape of the current, causing the kva taken by the rectifier to exceed its kw input, although the current is in phase with the voltage. In a 6-phase rectifier the power factor has the value 0.955. When the anode currents are delayed at constant load by an angle x_o, the primary current is simply shifted bodily by the same angle x_o, whereby the power factor is multiplied by $\cos x_o$. The curve of power factor against angle of delay is shown in Fig. 15, which shows that, for values of x_o greater than 30 deg, the power factor becomes poor. This shift of the current does not change the losses in the rectifier or in the transformer, so that the efficiency may be computed in function of x_o. At 600 volts these losses are of the order of 5.5 per cent of the unregulated output E_dI. When the anode currents are retarded by an angle x_o, the output becomes $E_dI \cos x_o$, and the efficiency decreases to

$$\frac{100\cos x_o}{(100\cos x_o + 5.5)} \tag{34}$$

This value is also plotted in Fig. 15, which shows that the efficiency remains acceptable over a wide

range of values of x_o. A moderate degree of regulation can therefore be obtained by grid control without adversely affecting the characteristics of the rectifier. If a wide regulation is utilized at infrequent intervals, as for starting a constant voltage bank of electrolytic cells at reduced voltage, the low efficiency and power factor may be unimportant. When a widely variable number of cells is to be fed continuously, high power factor and efficiency may be restored by combining a coarse regulation by tap changing with only a fine regulation by means of grids.

Inductive Interference

In systems adjacent to extensive communication circuits the probability of inductive action of the power circuits on the communication circuits should be considered. In general, as appears from Figs. 10, 11, and 12, grid control increases the magnitude of the a-c components of the continuous voltage, but the involved laws of variation of these harmonics make it necessary to consider each case separately. Let the case be considered of a 60-cycle 6-phase rectifier with interphase transformer, operating at an unspecified voltage, and assuming that a flat characteristic is desired up to full load at the unregulated full-load value of voltage. The inherent regulation of the rectifier net voltage will be somewhat as follows:

Regulation due to 5 per cent reactance	2.5 per cent
Increase in arc drop from no load to full load	0.75 per cent
Resistance drop in transformer windings	1.75 per cent
	5.00 per cent

The voltage should then be maintained at 95 per cent of the net no load, or rather, transition voltage. The telephone interference factor TIF of the output voltage is given by the formula[11]

$$TIF = \frac{\sqrt{\Sigma(H_nW_n)^2}}{E_d}$$

where H_n is the rms value of the harmonic of order n, W_n a factor called weighting factor, and E_d the rms output voltage, for which the average value will be substituted as x_o will be small. When the voltage is not regulated, $E_d = E_{do}[1 - (X_w/2)]$ and

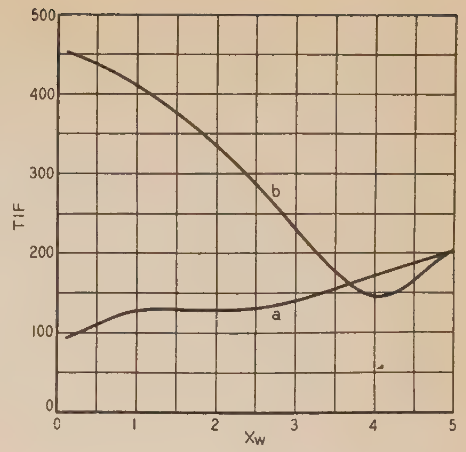


Fig. 16. Telephone interference factor (TIF) of a 6-phase 60-cycle rectifier with interphase transformer con- connection

a—Without regulation
b—With flat regulation

$$TIF = \frac{\sqrt{\Sigma\left(\frac{H_n}{E_{do}}\right)^2 E_{do}^2 W_n^2}}{E_{do}\left(1 - \frac{X_w}{2}\right)} = \frac{\sqrt{\Sigma\left(\frac{H_n}{E_{do}}\right)^2 W_n^2}}{1 - \frac{X_w}{2}} \tag{35}$$

When the voltage is regulated $E_d = 0.95\ E_{do}$ and

$$TIF = \frac{\sqrt{\Sigma\left(\frac{H_n}{E_{do}}\right)^2 W_n^2}}{0.95} \tag{36}$$

The TIF values given by formulas 35 and 36 are plotted in Fig. 16 against the working reactance, but include only the sixth, twelfth, and eighteenth harmonics given by Figs. 10, 11, and 12, affected by weighting factors of 700, 3,300, and 16,300, respectively. The value of x_o is maximum at transition load, at which TIF is also maximum. Grid control, however, causes a decrease of TIF at some loads because the eighteenth harmonic, the most disturbing from a 60-cycle supply frequency, decreases for increasing values of x_o at certain values of X_w. If a greater degree of regulation is desired, the maximum TIF will be correspondingly greater, but its value can always be reduced to a reasonable figure by means of filters.

Current-Interrupting Grids

In the above considerations it was assumed that the grid could only prevent the initiation of the anode current when negative, and release the current upon becoming positive, without having any action on the current after its establishment, thus acting as a trigger for starting the anode during each cycle. This type of grid is in general use at present. It has, however, been determined[16] that when the grid has certain dimensions it can regain control of the arc upon again being made negative. The interruption of the arc occurs with extreme rapidity; if each grid is energized positively only during the firing period of its anode, each anode current is interrupted instantly while the following anode current is released, and the anode currents follow each other without any overlap. The output voltage

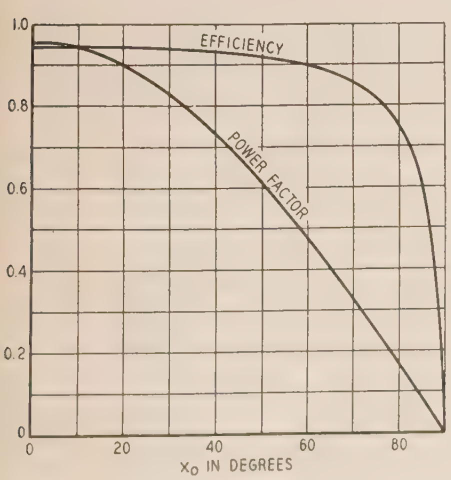


Fig. 15. Approximate efficiency and power factor of a grid-controlled 6-phase 600-volt rectifier at full load

under load with delayed anode operation will then have the aspect shown in Fig. 5b.

Instead of utilizing the falling branch of each anode voltage curve, it is also possible, by the action of this type of grid, to utilize the rising branch; each anode is then followed by an anode of lower voltage, as cannot be done when the current is simply allowed to pass from one anode to another. The anode currents then lead the anode voltages, and the alternating line current is drawn at leading power factor.

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A Survey of Hydroelectric Developments

A general outline of the status of modern hydroelectric developments is presented in this report by an A.I.E.E. subcommittee.* Major topics discussed are: developed water power of the world, present trends in utilization of water power, and hydraulic and hydrodynamic research. It is hoped that this report not only will present a retrospective picture of results achieved, but also will serve as a source from which general information can be obtained and conclusions drawn concerning modern trends of hydroelectric developments.

NORMAL GROWTH of the electric power generation industry was retarded considerably during the last few years. Furthermore, the nature and extent of future growth does not seem to be very clear, particularly so far as hydroelectric developments are concerned. Under such conditions it seems to be very timely to take stock of the results achieved and to outline the present status of modern hydroelectric developments. This survey is an attempt to give such an outline. It is hoped that the survey not only will present a retrospective picture, but also will serve as a source from which general information can be obtained and conclusions drawn concerning the modern trends of hydroelectric developments.

So far as possible, this survey was kept on an international basis; and although the United States and Canada take the most prominent part in the survey, all information pertaining to other countries that could be made available and was considered of interest is included. The survey is not 100 per cent complete, but an effort was made to include all important factors, based mostly upon authentic data supplemented in some cases by reasonable estimates and interpretations of such data.

The international character of the survey was made possible by the splendid assistance given by the foreign membership of the subcommittee.

Editor's Note: Extended statistical section of this report not ready in time for publication in this issue: scheduled for inclusion in the July issue.

Present Trend in Utilization of Water Power

Utilization of water power is governed by the basic requirement of delivering energy economically to localities where a demand for such energy is present or can be created. The flow of water in any stream shows variations even if the stream is regulated by large natural lakes. Flow variations in streams that do not have such natural regulation may become very large. The economy of a water power

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* Subcommittee on hydroelectric survey of the A.I.E.E. committee on power generation: A. V. Karpov, chairman, Pittsburgh, Pa., F. A. Allner, Baltimore, Md., E. W. Dillard, Boston, Mass., J. P. Hogan, New York, N. Y.; J. Elmer Housley, Alcoa, Tenn., A. H. Hull, Toronto, Ont., Can., S. Kloumann, Oslo, Norway, Jean Leclerc du Sablon, Toulouse, France, C. F. Mackness (deceased), London, Eng., J. M. Oliver, Atlanta, Ga., R. E. B. Sharp, Philadelphia, Pa., J. E. Stewart, Pittsburgh, Pa., and K. Tsuruta, Tokyo, Japan.

Mr. André Henry-Côuannier, civil and mining engineer, assisted by Mr. Roger Deshayes, engineer E.S.E. (Ecole Supérieure d'Electricité) both of Paris, France, were instrumental in collecting the data pertaining to the production of hydraulic turbines in Europe. The map showing the major hydroelectric developments of the North American continent was prepared by Mr. F. K. Mayhood.

development depends largely on the degree of utilization of the available water, optimum utilization being obtained with synchronization of flow and energy demand. The most obvious method of accomplishing this is to create an artificial water storage to regulate the stream flow so as to make water available at all times to supply the energy demand. In any water power development, a certain amount of storage is created by the building of a dam and impounding water back of it. Only in very rare cases, however, can such incidental storage have much regulating influence. In practically all cases the creating of artificial storage large enough to regulate the flow satisfactorily will require a heavy expenditure. In localities that are well suited for use as storage sites, as for instance in Switzerland and some parts of Canada, such natural advantages usually are fully utilized.

The Boulder Dam plant, now under construction on the Colorado River, is the most outstanding example of a plant on a river having extreme flow fluctuations that will be regulated artificially for irrigation and power purposes; these fluctuations will be regulated to an extent never previously attempted and that probably will not be repeated for many years on such a scale.

In many cases the cost of the desirable amount of storage is prohibitive, and best economy is obtained by partial regulation of the water flow and complementary adjustment of the energy demand.

Influence of Electrochemical and Electrometallurgical Industries

In the last few decades several industries using large amounts of electric energy were developed. The modern trend decidedly favors the substitution of processes based upon the utilization of electric energy for the purely chemical processes previously used. The manufacture of hydrogen and the electrical methods of producing aluminum oxide from bauxite, the basic ore, are a few of the indications of that trend. The processes in most of these industries are of such character that the energy demand can be adjusted within wide limits.

Energy cost is a major factor for an industry using large quantities of electric energy per unit of product, so that it may be economical to locate the production plant close to a source of cheap electric energy even though the location may be remote from the source of raw materials and from the market for the finished product.

The financing of most of the water power developments in outlying poorly populated districts, was made possible only by the demand for electric energy that was created by such industries. This not only turned the wasted water energy to useful purposes, but incidentally resulted in these districts becoming modern highly developed communities.

The latest developments at the upper part of the Saguenay River in Canada are quite representative in that respect. The Saguenay flows from the Lake St. John, which acts as a natural regulator of the water flow of the river, and consequently the flow fluctuations are somewhat moderated. The plants already built or proposed on that river are to supply large blocks of power to electrometallurgical and paper industries. The economical justification of these developments is based upon the fact that the power demand of these industries may be regulated so that for the largest part of the time the demand will be synchronized with the available supply of energy.

The recent considerable increase of developed water power in Norway follows along the same line. The utilization of the vast available, but undeveloped, water powers of the Asian mainland, of Africa, and of South America in all probability will be made possible by the same gradual process of establishing industries demanding large blocks of cheap electric energy.

The Dneiperstroy development, on the Dneiper River in Russia, is a sample of such a development built on a very flashy river with a limited amount of artificial regulation. The economical justification of this development is based upon the expectation that the power demand of the industries yet to come can be regulated to the necessary extent.

Interconnections

A hydroelectric plant located in an outlying district and supplying energy in large blocks to a limited number of industries has primarily the one purpose of transferring the maximum possible amount of available water power into useful energy. A hydroelectric plant located in close proximity to populated or highly industrialized districts has to carry a diversified utility load; this means the supplying of the necessary amount of energy when the demand occurs. The economical operation of such plants is made possible by the wide use of interconnections.

In the past it was a common practice to operate plants independently. Even at present they may be operated in such way if the industrial energy demand can be suitably regulated. However, the modern trend is to make hydroelectric plants links in power systems to obtain better economy in supplying increased energy demands.

The advantages of interconnection are such that no development of any importance can overlook them, and even if an immediate interconnection between existing systems cannot be justified, the way is left open for future interconnections. Consequently, all developments of appreciable size put into operation during the last decade were alternating current developments even in cases where the bulk of the generated electric energy had to be transformed into direct current for the ultimate use in the electrochemical or electrometallurgical industries. The Lochaber direct current development of the British Aluminum Company is the only exception.

Interconnections provide economical and operating benefits that sometimes make it possible to break through territorial boundaries. The interconnections between the power systems of Switzerland and those of France, Germany, Austria, and Italy, are the most outstanding instances of an in-

ternational widespread interconnected energy supply system.

Present interconnected systems are of different character. The combination of many water power developments of different kind and character often located on different drainage basins, some with storage capacity and some without, may result in a satisfactorily regulated system even without including any thermal plants in the system.

The developments that are combined by the Hydroelectric Power Commission of Ontario may be cited as an example. Here the backbone is formed by the Niagara Falls developments, and the utilization of the system is improved by supplying blocks of power to industries the power demand of which can be regulated.

In most cases the interconnected systems include thermal as well as water power plants. The systems located in the western part of the United States and the interconnected plants in Sweden may be cited as interconnections in which the main part of energy is supplied by hydroelectric plants.

During later years hydroelectric developments are gaining in importance in such localities, as, for instance, the eastern part of the United States, where very large loads are carried by thermal plants.

Capacity needed for short periods to meet peak load requirements often may be provided economically in hydroelectric plants. The comparatively small increment cost of additional capacity of hydroelectric plants makes it advantageous to provide equipment many times in excess of the average load. If such plants are operated only a limited number of hours comparatively large peak loads can be handled. The recent Susquehanna River developments at Conowingo (Md.) and Safe Harbor (Pa.) are typical not only in that respect, but also as developments that could not be justified economically without a previously developed large thermal capacity.

In systems having relatively large thermal capacities, the hydroelectric plants may fulfill advantageously several functions in addition to the main one of supplying electric energy. In a modern hydroelectric plant a unit may be started from standstill, brought to proper speed, synchronized, connected with the system and deliver its rated capacity within a very few minutes. A steam unit under stand-by conditions may pick up the load quickly, but ordinarily requires a long time if both boilers and unit are cold. Consequently the hydroelectric unit is better adapted for stand-by service or for use as a spare unit. Very often the stand-by characteristics are improved by having the unit permanently connected to the system, idling the turbine and utilizing the generator as a synchronous condenser, to improve the electrical characteristics of the system.

The energy consumption of such idling units is reduced sometimes by automatically breaking the vacuum or by forcing the water from the turbine runner by means of compressed air. If a failure occurs in some part of the system, such an idling unit may be loaded to full capacity within a few seconds.

Pumped Storage Plants

In the past, small pumping plants were used in high head European developments. These plants did not operate on a complete pumping cycle, but collected in a single intake the water of several small streams. Since usually the pumping head was low compared with the total head, the resulting increase of the plant output was much larger than the amount of energy spent in pumping. At present the use of pumped storage plants operating on a complete pumping cycle is rapidly gaining in importance, due to the wide use of interconnections.

The economical value of energy to a system having daily or seasonal load peaks depends to a large extent on the time at which the energy may be made available. If the power demand cannot be synchronized entirely with the available power, then the power required to meet peak load conditions has a high value, whereas the excess of power available during low load periods has a much lower value.

It may be economical to increase the utilization of the available storage capacity by using a pumping scheme. In spite of the fact that under average conditions the efficiency of a complete pumping cycle is only about 60 per cent, it may be economical to invest 100 kwhr at times of low demand to secure a return of 60 kwhr when energy is needed badly.

Most of the pumped storage plants are located in Europe, the Rocky River (Conn.) development being the only plant of appreciable size in the United States. Some of these plants are located in Switzerland, being used to cover the season deficiency of power. Several are located in Germany and France, being used to take care of the daily peaks. It is of interest that one of the largest pumping storage plants located at Niederwartha near Dresden in Germany is built to meet the peak load requirements of a purely thermal system. The economical justification of such a scheme is based upon the high over-all efficiency of a steam plant with base load operation and the low aggregate steam plant capacity that may be well below peak load demands.

In spite of the small storage capacity of the Safe Harbor plant, it is proposed to take care of the anticipated increase of the peak load of the system to which that plant supplies power by introducing a pumping cycle at Safe Harbor, using steam power for pumping, instead of increasing the steam generating capacity.

Economy in Design and Operation

Considerable advance was made during the past few years in improving the economy of modern developments. Work in that direction still goes ahead on all important phases, the tendency being to reduce the first cost, to improve the over-all efficiency, and to reduce the cost of operation.

So far as the structural design is concerned, more economical designs of gravity and arch dams are possible if knowledge is increased regarding the actual distribution of stresses in dams. In that respect the most extensive study was made on arch dams, by means of measurements made on such dams and

by several model studies. This work should result in safer and more economical designs of such dams.

In power plant design the most important economy was achieved along 2 lines: first, the increase of the size of units, and second, the increase of specific speed in particular of units for low head developments. Both are results of extensive theoretical and experimental studies, and in all probability future improvements in these directions are possible.

The extensive use of interconnections made it possible to improve the utilization of the available water energy by increasing the installed power plant capacity.

For an isolated hydroelectric plant the economical capacity usually will correspond fairly closely to the average water flow. Under ordinary conditions, the interconnection of several hydroelectric plants will increase the economical capacity of each plant. Finally, for hydroelectric plants that are linked to a large thermal system, the economical capacity may be still higher and will approach more closely the capacity corresponding to the maximum flow.

So far as improvement in efficiency is concerned, the efficiencies of some of the hydraulic units approach 94 per cent at their best points, so that not much opportunity is left for further improvement in that direction. The main efforts are directed toward the improvement of efficiency for conditions of head and loading different from that of the maximum efficiency.

Both Pelton and Francis turbines sometimes are installed in plants having sufficiently high heads. Then the Francis turbines carry the base load at favorable efficiency conditions and the Pelton turbines, having the better efficiency at part loadings, carry the fluctuating loads. For medium head developments Francis turbines of different characteristics sometimes are used, again adding to the over-all efficiency of the plant.

Introduction of the Kaplan turbine, with its very flat efficiency curve under different load and head conditions, puts low head developments in a favorable position so far as average efficiency is concerned. Since Kaplan turbines may be overloaded considerably without an undue reduction of efficiency, it is possible in large installations to reduce the cost by the elimination of spare units. In such cases the electric generators have to be of larger size so that in case of failure of some of the units the rest of them can be used to carry the same total load. The introduction of a pumping scheme in some cases may be the next step in improving the over-all economy of a development.

Reduction of operating cost has been very much influenced by the introduction and successful operation of automatic and semi-automatic plants.

The 54,000-hp Alexander development on the Nipigon River in Canada, represents the largest automatic plant put into operation to date. Experience gained in the design and operation of automatic plants is being utilized to a large extent in manually operated plants. Many of the different remote control systems used in automatic plants are being applied at least partly to manually operated plants, centralizing the control of the plant at a very few places, reducing the size of the operating crew, and insuring a safer, more nearly perfect, and more economical operation.

Hydraulic and Hydrodynamic Research

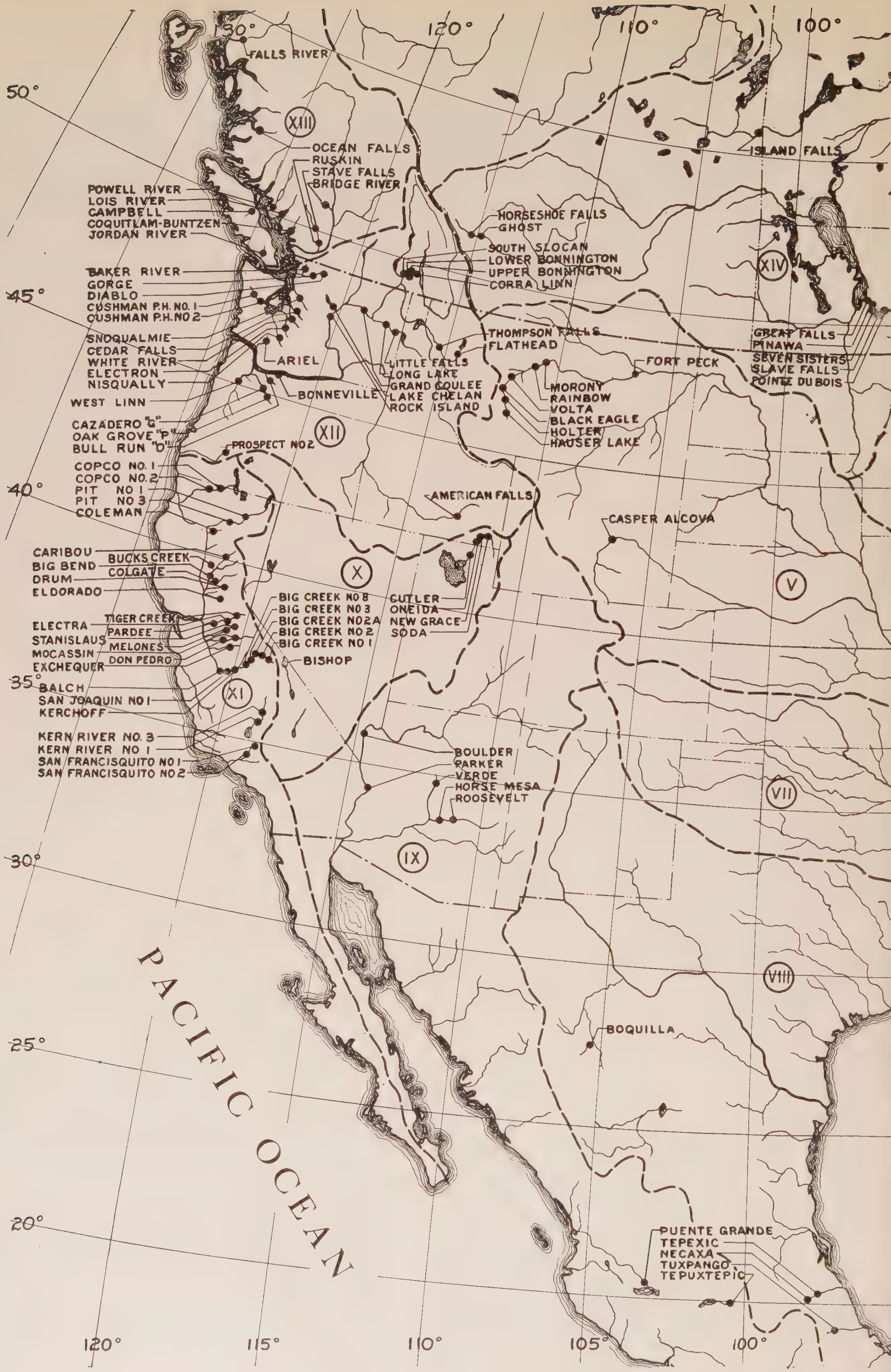
The necessity of extensive hydraulic laboratory research for the economical design of hydraulic structures was realized some time ago. The latest development of turbines of high specific speed stressed the necessity of extended hydrodynamic research.

In some European countries, particularly Switzerland, Germany, and Sweden, several laboratories have been operated and an extensive study conducted along the lines of both hydraulic and hydrodynamic research.

In the United States the Massachusetts Institute of Technology gave a new impulse to such research by starting a series of lectures by the well-known authorities, de Thierry, Rehbock, Thoma, and Spannhake. The late John R. Freeman was responsible to a great extent for the increased activity in the scientific study of hydraulic problems as well as in the creation of the national hydraulic laboratory at Washington, D. C., which is expected to take an important part in the study of such problems. Numerous other laboratories in the United States and Canada make it possible at present to study experimentally the hydraulic problems that are so plentiful in connection with new or existing water power developments.

The importance of high specific speed turbines was realized in the United States some time ago; but only lately came the realization that advanced design of such turbines necessitated extensive research in hydrodynamics and particularly the study of cavitation. These ideas were promoted by far-seeing individuals, the A.I.E.E. and other engineering societies taking their share in that movement by making possible the presentation and discussion of papers in which the hydrodynamic research problems were particularly stressed.

L. F. Moody and F. H. Rogers have done important pioneer work in the development of the cavitation theory, but construction of cavitation laboratories lagged considerably until the recent opening by the Safe Harbor Water Power Corporation of the complete cavitation laboratory at Holtwood, Pa. Additional commercial laboratories of this type now are being undertaken. Fundamental theoretical research in that direction is made possible by the opening in 1932 of the first scientific cavitation laboratory in the United States at the Massachusetts Institute of Technology. During his visit to the United States, Doctor Thoma was instrumental in forming plans and ideas for the building of both the Holtwood and the M.I.T. laboratories. The last named laboratory is the direct result of the work of Doctor Spannhake. In spite of the short time that this laboratory has been in operation, studies of theoretical interest and of practical importance have been made particularly in regard to pressure distribution in cavitation areas.


FALLS RIVER
OCEAN FALLS
RUSKIN
STAVE FALLS
BRIDGE RIVER
POWELL RIVER
LOIS RIVER
CAMPBELL
COQUITLAM-BUNTZEN
JORDAN RIVER
HORSESHOE FALLS
GHOST
SOUTH SLOCAN
LOWER BONNINGTON
UPPER BONNINGTON
CORRA LINN
BAKER RIVER
GORGE
DIABLO
CUSHMAN P.H. NO. 1
CUSHMAN P.H. NO 2
SNOQUALMIE
CEDAR FALLS
WHITE RIVER
ELECTRON
NISQUALLY
WEST LINN
ARIEL
BONNEVILLE
LITTLE FALLS
LONG LAKE
GRAND COULEE
LAKE CHELAN
ROCK ISLAND
THOMPSON FALLS
FLATHEAD
FORT PECK
MORONY
RAINBOW
VOLTA
BLACK EAGLE
HOLTER
HAUSER LAKE
ISLAND FALLS
GREAT FALLS
PINAWA
SEVEN SISTERS
SLAVE FALLS
POINTE DU BOIS
CAZADERO "G"
OAK GROVE "P"
BULL RUN "O"
PROSPECT NO 2
COPCO NO. 1
COPCO NO. 2
PIT NO 1
PIT NO 3
COLEMAN
AMERICAN FALLS
CASPER ALCOVA
CARIBOU
BIG BEND
DRUM
ELDORADO
BUCKS CREEK
COLGATE
BIG CREEK NO 8
BIG CREEK NO 3
BIG CREEK NO 2A
BIG CREEK NO 2
BIG CREEK NO 1
CUTLER
ONEIDA
NEW GRACE
SODA
ELECTRA
TIGER CREEK
PARDEE
STANISLAUS
MELONES
MOCASSIN
EXCHEQUER
DON PEDRO
BISHOP
BALCH
SAN JOAQUIN NO 1
KERCHOFF
KERN RIVER NO. 3
KERN RIVER NO 1
SAN FRANCISQUITO NO 1
SAN FRANCISQUITO NO 2
BOULDER
PARKER
VERDE
HORSE MESA
ROOSEVELT
BOQUILLA
PUENTE GRANDE
TEPEXIC
NECAXA
TUXPANGO
TEPUXTEPIC
PACIFIC OCEAN
XIII
XIV
XII
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110°
100°
115°
105°

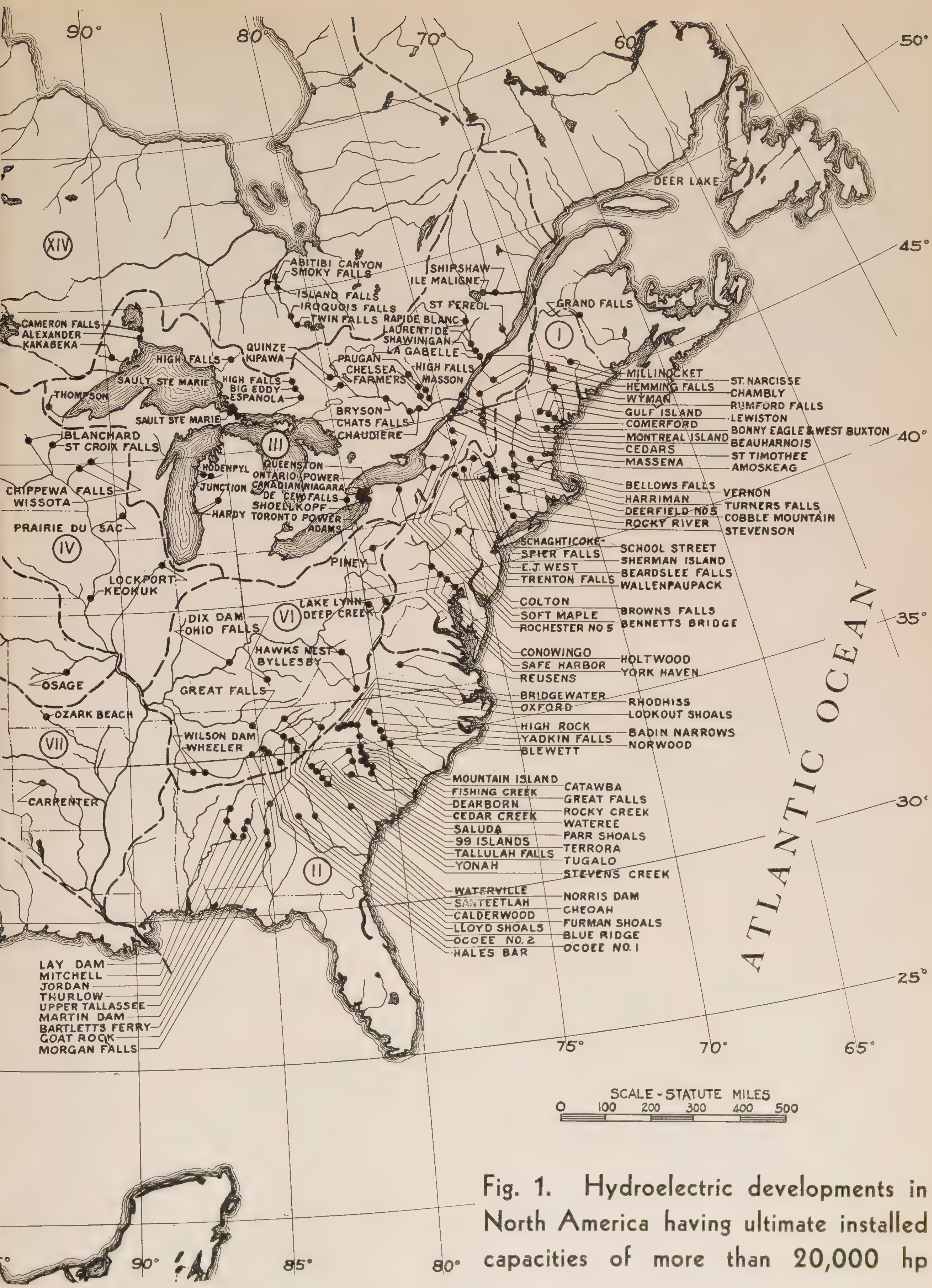

Fig. 1. Hydroelectric developments in North America having ultimate installed capacities of more than 20,000 hp

A 7,000-Ampere Station Bus

Inductive heating and space limitations complicated the problem of redesigning a 4,000-amp bus to carry 7,000 amp, without structural changes in existing cells and runways. A general discussion of the unusual problems involved is given in this paper, together with the methods of solution and supporting test results.

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INITIALLY, the development at the Richmond Generating Station of the Philadelphia Electric Company consisted of 2 50,000-kw 80 per cent power factor 13,800-volt 60-cycle turbine-generators; later these were re-rated to 60,000 kw. Space was provided and reserved at each end of the building for one additional unit of the same capacity.

These initial units were connected to a 13.2-kv vertically isolated phase bus located in a separate switch house along with its associated switching equipment. This bus was of the conventional flat bar construction, designed for 4,000-amp maximum capacity, and consisted of 7 $4x^1/_4$-in. bars at the center tapering to 3 $4x^1/_4$-in. bars at the ends. The generator leads were of similar construction, designed for 3,000 amp and consisted of 3 $5x^1/_4$-in. bars housed in concrete compartments. Identical lead compartments were provided for the future units.

The General Problem

When conditions indicated the need of additional generating capacity, economic studies showed the necessity of taking advantage of recent developments in turbine design by installing a unit of greater physical dimensions and considerably greater capacity than was originally contemplated. Accordingly, a new 165,000-kw 90 per cent power factor 13,800-volt turbine-generator was purchased.

Thus, it became necessary to install a 165,000-kw machine and its accessory devices in an existing building in space originally intended for a 50,000-kw unit. The installation of the new machine required:

1. That the capacity of the isolated phase main bus be increased from 4,000 to 7,000 amp at 60 cycles, meanwhile adhering to the original enclosure dimensions of 24x24 in. and maintaining necessary electrical ground clearance.

2. That the new generator lead runs, designed to carry 5,000 amp per phase, be installed in enclosures originally designed for 3,000 amp per phase and having general dimensions of 24x24 in. but varying in width and height to as little as 21 and 17 in., respectively.

3. That all steel members in the vicinity of the above conductors be protected from dangerous temperatures resulting from magnetic induction.

These structural restrictions resulted in the 7,000-amp main bus passing concrete-fireproofed structural members with clearance of 16 in. and 5,000-amp generator lead runs having corresponding clearances as low as $4^7/_8$ in. The increased range of effect of the higher currents also brought minor miscellaneous steel, such as framing and supports for the bus and lead-run enclosures, metallic doors and door framing, etc., well within the magnetic influence of the conductors.

Thus, 2 major problems were involved in the consideration of the bus: first, the selection of a satisfactory conductor; and second, the prevention of inductive heating, or its reduction to harmless values. As a result of extensive laboratory and other tests, the following conclusions were reached:

1. For conductors to carry heavy currents and to be installed in restricted space, the 2-piece copper channel construction described in this paper has outstanding advantages.

2. With the continually increasing tendency toward larger generating units and greater concentrations of energy, protection against inductive heating will become an important factor in station design and must be given definite consideration. Where adequate spacings are not obtainable and other expedients are not feasible, the judicious application of short circuited bands and amortisseur grids will greatly reduce the heating.

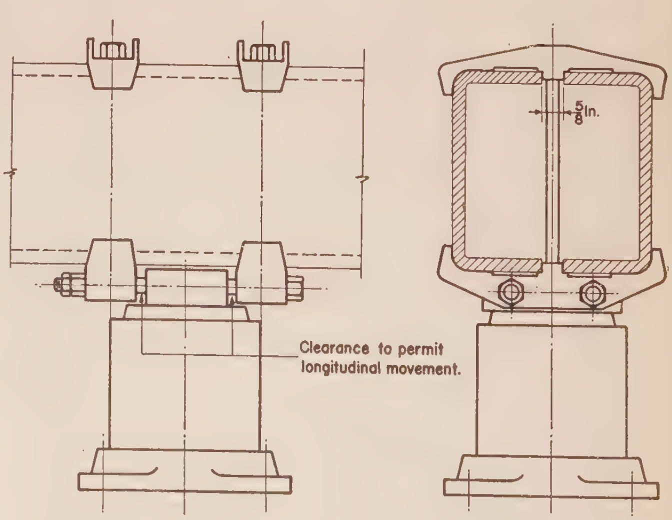


Fig. 1. Sliding clamp bus support for copper channel

Full text of a paper recommended for publication by the A.I.E.E. power generation committee, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted April 9, 1934; released for publication April 30, 1934. *Not published in pamphlet form.*

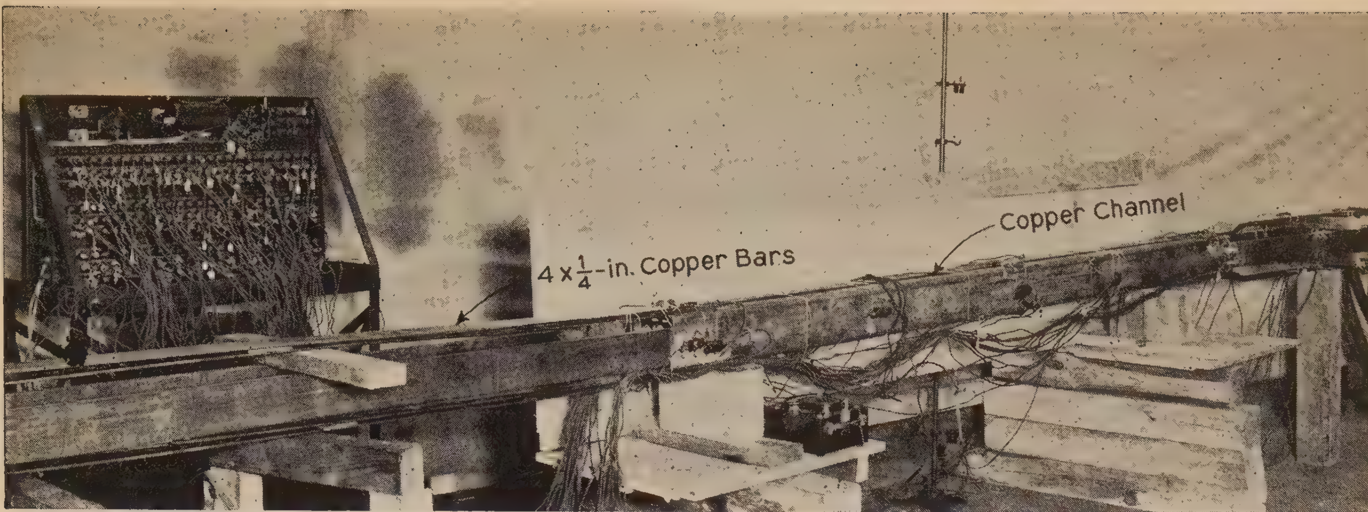


Fig. 2. Copper channel bus ready for a-c resistance test

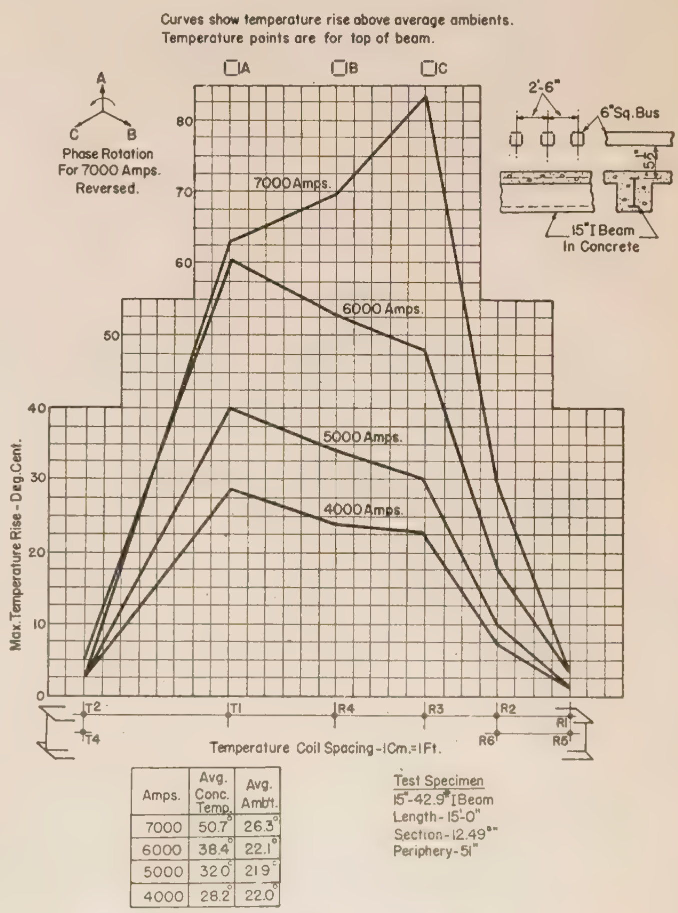
Although no attempt has been made in this investigation to formulate generalized laws covering the phenomena of inductive heating, there has been accumulated a mass of elemental data suitable for abstract study and development by those theoretically inclined. It is felt, however, that the information in this paper will provide a useful if not infallible guide for the solution of similar practical problems.

Selection of Conductor

The size of the conductor for main bus and lead runs was limited by the necessity of maintaining adequate ground clearance in the restricted enclosure space. Low resistance was greatly to be desired because the complete enclosure of these conductors forced serious consideration of the means of disposing of the resistance heat losses. The use of cables for the generator leads was impracticable because of lack of space for ducts and manholes.

Multiple flat copper bars to carry currents of 5,000 and 7,000 amp were not feasible because of the diminishing value of additional bars above 5,[1] and the large number of bars necessary could not be accommodated in the space available. Flat copper bars arranged in a hollow square have been used for carrying heavy currents,[2] but this involves complicated fittings for clamping the conductors in position and for making heavy current taps. Inability to maintain ground clearance, particularly at certain beam crossings and at connections and taps to the main bus, precluded the use of this construction.

The most economical section for a heavy-current conductor is of course a hollow cylinder. Published data indicated that the optimum wall thickness is approximately $1/2$ in.,[1] and further that a copper tube to carry 5,000 amp would be approximately 6 in. in diameter, even with this special wall thickness. This in itself was not objectionable but the fittings for splices and taps are necessarily bulky and, in the limited space available, it was impossible to maintain the established minimum ground clearance. These disadvantages were even more pronounced in the case of the 7,000-amp main bus. An effort was made to increase the capacity and thus reduce the size of tubular conductors by cutting slots in the top and bottom. A superficial test showed that the small amount of air circulation provided by this means did not result in material improvement. Heavy-current conductors consisting of 2 aluminum channels have been used to some extent, but it was found that the dimensions of such channels to carry the currents



Amps.	Avg. Conc. Temp.	Avg. Ambt.
7000	50.7°	26.3°
6000	38.4°	22.1°
5000	32.0°	21.9°
4000	28.2°	22.0°

Fig. 3. Shift of hottest spot in I-beam by reversal of phase rotation

1. For numbered references see bibliography at end of paper.

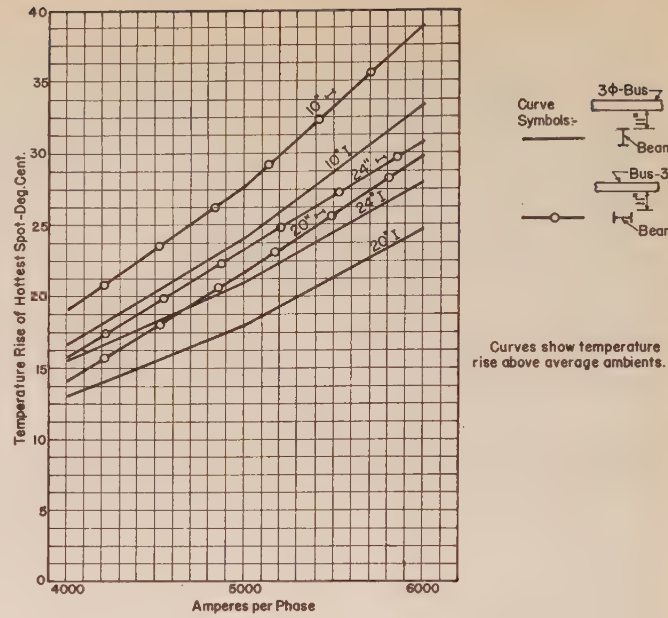
involved were too great for the space limitations to be encountered.

The use of copper conductors fabricated in special channel sections assembled to form practically a hollow square offered considerable promise. In order to be economical of metal, it was desirable that the thickness be uniform and approximate the optimum thickness of $^1/_2$ in. Such channels were naturally new. No quantitative data were directly obtainable as to a-c resistance, ability to dissipate heat, or current rating. The method of manufacture was uncertain, and the necessary tolerances to permit their use would have to be determined.

Preliminary calculations indicated that for currents of from 5,000 to 7,000 amp the channels should be approximately 8-in. in height, and for currents from 3,000 to 5,000 amp a 6-in. height was indicated.

The usual $^1/_4$-in. copper bars are relatively flexible, and will bend to compensate for variations in size and alignment in splicing, and will bow without imposing excessive strains on supports. On the contrary, the proposed bus forming a hollow box 6- to 8-in. square and $^1/_2$-in. thick would be extremely rigid in torsion and bending, as well as in column action, so that definite provisions would have to be made to take care of longitudinal thermal expansion. (Fig. 1.)

Sections of the size and uniform thickness desired could not be obtained by mere adjustment of the rolls used for producing structural shapes. The amount of conductor involved could not carry the added expense of design and manufacture of special rolls. Limitations of size and straightness are of minor importance in the use of structural rolled sections but the splicing of these heavy copper sections imposes severe restrictions on dimensions and straightness. This was accomplished by using plates of carefully selected material, rolled and cut to closely controlled dimensions, and finally drawn through dies to form and size the product.

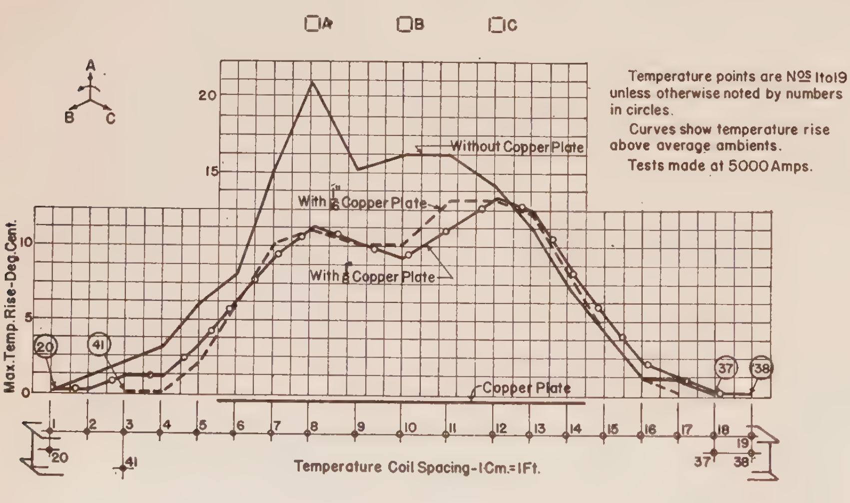


	Test Specimens		
	10"-25.4#	20"-70#	24"-79.9#
Length	20'-0"	20'-0"	20'-0"
Section	7.38□"	20.42□"	23.33□"
Periphery	38"	64"	75"

Fig. 5. Temperature rise in I-beam vs current, size, and position of beam

Table I

Item	Conductor	Section Sq In.	Resistance, Ohms Per Ft × 10^{-7} D-C	A-C
1....4	6x$^1/_4$-in. and			
4	4x$^1/_4$-in. bars in hollow square	10.0	8.510	11.70
2....4	5x$^1/_2$-in. in hollow square	10.0	8.510	11.21
3....2	6x0.490-in. copper channels	9.88	8.617	12.00
4....2	8x0.470-in. copper channels	13.28	6.409	8.65



Copper Plate Thickness	Max. Plate Temp.	Avg. Ambt.
None	None	21.9°
1/16"	61.0°	21.9°
1/8"	49.0°	24.8°

Fig. 4. Shift of hottest spot in I-beam by interposition of copper plate

Carrying Capacity

A great amount of theoretical investigation of "skin effect" in cylindrical hollow or solid conductors has been done by H. B. Dwight and others, and their data have been, to some extent, substantiated by experience.[3] However, no reference could be found on the calculation of the "skin effect" for hollow sectional conductors having rectangular outlines.

In order to determine the magnitude of this effect, the formulas, curves, etc., evolved by Dwight were used for the hollow square arrangements, assuming that the ratio of thickness to diameter for a cylindrical conductor could be replaced by the ratio of thickness to the side of the square in the case of a hollow square conductor. With this assumption, the values of 60-cycle a-c resistance at 60 deg C of several conductor shapes were computed and are shown in Table I.

From these calculated resistances, the expected conductor losses were obtained.

The manufacturer rated the 6-in.

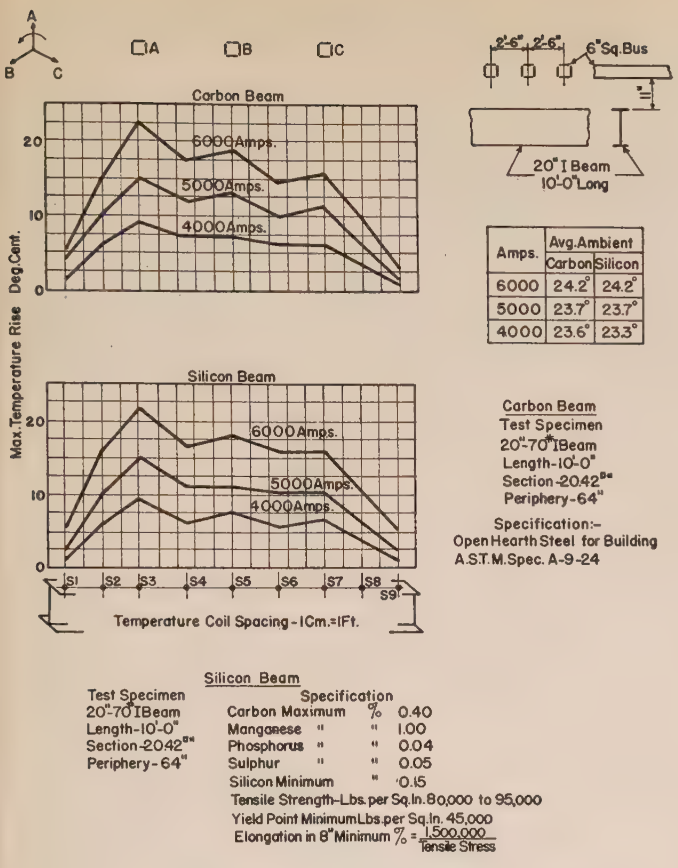
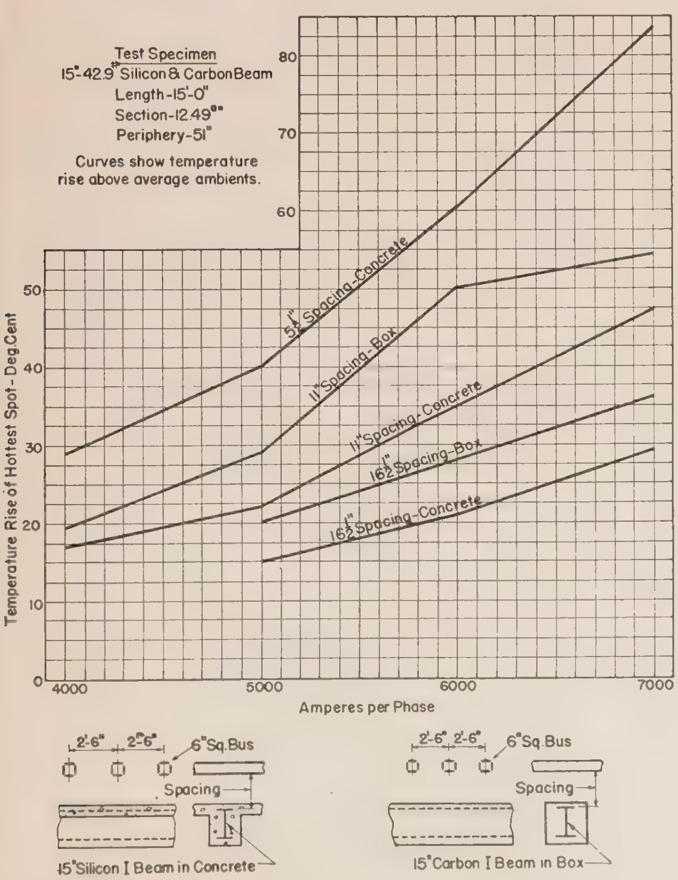


Fig. 6. Comparison of inductive heating characteristics of carbon and silicon steel I-beams

Fig. 7. Temperature rise in I-beam vs current and clearance



copper channels at 5,000 amp in the enclosures to be used, and the 8-in. channel at 7,000 amp, based entirely on calculations. However, observation of temperature conditions in existing conductor runs indicated that due to the unsatisfactory heat dissipating qualities of the enclosures, the losses from the increased currents would probably necessitate forced ventilation even with the most favorable conductor obtainable. Laboratory tests were made on sample conductors 10-ft long to determine experimentally the current carrying capacity. The current was led into the channel sections by 8 $4x^1/_4$-in. bars in a hollow square arrangement for the 6-in. channel and 12 $4x^1/_4$-in. bars in the case of the 8-in. channel. (Fig. 2.) This provided an opportunity to directly compare the temperature rise of the built-up $^1/_4$-in. bars with that of the channel. (Table II.) In order to gain some idea of the heating to be expected after installation in the concrete enclosures a test box was built from insulating board. Heating of the channels both in open air and in the box is also shown in Table II. Even though this box could not be considered as similar to the actual concrete structures, the heating confirmed the feeling that the problem of removing heat from the conductor enclosures would require forced ventilation. The crowding of current into the outer bars of the built-up hollow square arrangement is clearly shown by the temperatures observed.

The unsatisfactory heat dissipating qualities of the concrete enclosures increased the desirability of additional data on the heat losses to be expected, which in turn depended on the 60-cycle resistance. To measure directly the a-c resistance of large conductors of irregular section considerable difficulty and expense would be encountered, and even then the accuracy would be subject to question. An indirect method suggested by D. C. Prince was finally adopted. Briefly, a 10-ft sample of the channel assembly was set up with thermocouples liberally distributed over the surface. A heat run was made at the desired current until the temperature was steady, from which the average temperature rise was obtained. A cooling curve was then taken by further raising the temperature of the bus and, after quickly removing all connections, recording the

Table II—60-Cycle Heating of Copper Bus

Bus Channel	Bars	Cross Sec Sq In.	Amp	Temperature Rise in Deg C: Max	Min	Avg Outer Bars	Avg Inner Bars	Gen Avg
Copper channel in heat-insulated test box								
2	8 in.	13.28	7,000	51.5	39.5			48.3
2	8 in.	13.28	6,000	38.2	30.2			35.7
2	6 in.	9.88	5,000	37.3	31.3			35.0
2	6 in.	9.88	4,400	29.2	23.2			27.2
Copper channel in air								
2	8 in.	13.28	7,000	23.5	19.5			21.0
2	8 in.	13.28	6,000	17.8	13.8			15.3
2	6 in.	9.88	5,000	20.2	16.2			17.4
2	6 in.	9.88	4,400	14.2	12.2			13.0
$4x^1/_4$-in. copper bars, hollow square arrangement, in air								
	12	12.0	7,000	37.5	17.5	31.3	25.8	28.6
	12	12.0	6,000	27.8	11.8	23.8	19.4	21.6
	8	8.0	5,000	27.2	10.2	19.6	16.2	17.9
	8	8.0	4,400	21.2	7.2	13.6	12.0	12.8

time-temperature readings during the cooling period, and plotting the average temperature rise against time. The slope of this curve at any temperature is the rate of cooling and by combining this with the weight and specific heat of the channels, the Btu loss dissipated at that temperature is obtained. It is a simple matter to convert this to watts and, with the current known, to get the resistance.

Following is a comparison of the calculated and test values of 60-cycle resistance in ohms per ft:

	Calc. Res.	Test Res.
8-in. channels	8.65×10^{-7}	9.79×10^{-7}
6-in. channels	12.0×10^{-7}	13.78×10^{-7}

With the channels in open air, the cooling curves were exceptionally uniform. The results obtained were consistent but they were found to be from 10 to 15 per cent greater than the calculated values. An unsuccessful effort was made to check these results with the channels enclosed in the test box, but the heat inertia of the diverse parts of the thermal circuit caused inconsistent results.

Inductive Heating

Superficial calculations and tests indicated that total temperatures of 70 deg C (158 deg F) could be developed in a bare carbon-steel I-beam in open air when located at about 10 in. spacing inside of a 90 deg bend in a single-phase bus carrying 4,400 amp, and that greater temperatures might be expected for smaller clearances.

Although a total temperature of 70 deg C in open air did not justify great alarm, it did prompt speculations as to what temperatures and effects might be expected in the actual silicon steel structure, fireproofed with concrete:

1. Would the greater currents and smaller clearances result in intolerable temperature elevations?

2. Would the concrete tend to thermally insulate the hot spots or would it conduct the heat to the surface or to other sections and thus lower the hot-spot temperature?

3. Was there any likelihood that the temperatures might be high enough and so distributed as to cause expansion buckling between fixed points or so confined as to actually weaken the steel?

4. Could these high temperatures, resulting in unequal expansion, cause slippage between the steel and concrete, destroying the composite characteristics of the structure?

All of these were logical questions, based on fundamentals. Unfortunately, the gap between the questions and their answers could be bridged only by a chain of loosely connected and doubtful assumptions, making rational answers practically impossible. Assuming that dangerous temperatures would exist, such remedial expedients as multiple buses, bus transpositions, or increased physical clearance between buses and steel were quickly eliminated. This left but 2 choices: first, to provide for heat dissipation at rates which would prohibit excessive temperatures; and second, to prevent or diminish heating. The former was obviously expensive and unreliable. The latter, if capable of accomplishment, was direct in that it struck at the source of the difficulty and had possibilities of permanency. The

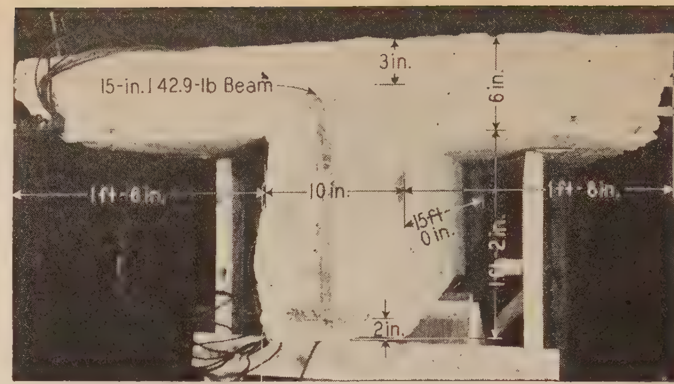


Fig. 8. Composite steel-concrete section used in tests

introduction of neutralizing fields by means of nonferrous short-circuited turns fell in the second class and held considerable promise.

These short-circuited turns could take either of 2 forms. They could be short circuited bands so placed around the steel that the plane of the band would lie in the plane of the current flow in the inducing conductor or they could take the form of amortisseur grids with their long axes parallel to that of the inducing conductor. While the use and characteristics of both of these expedients are old and well understood in machine design, the procedure for their application to a structural problem left much to be learned. Recourse to obtainable literature and

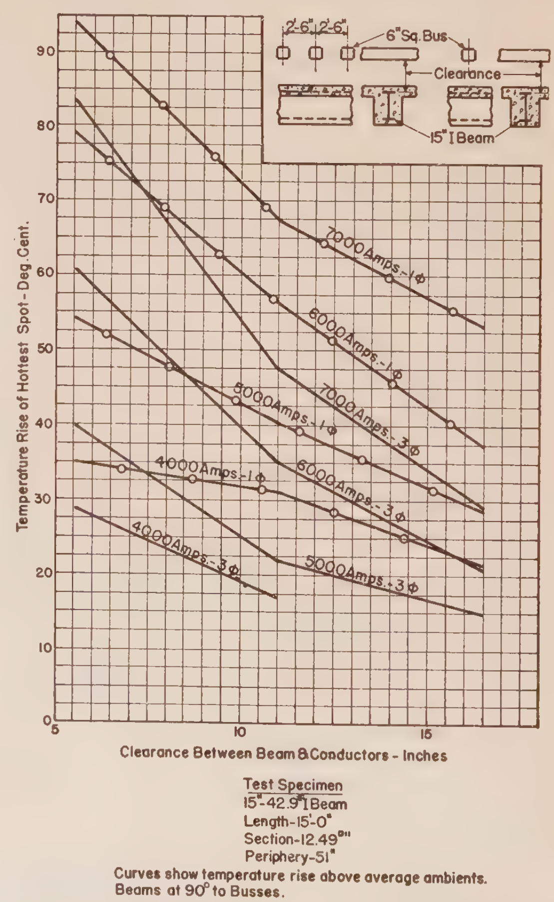


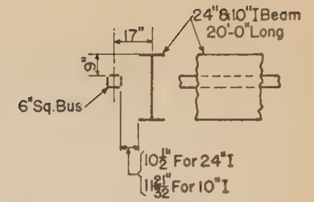
Fig. 9. Temperature rise vs current, clearance, and type of circuit for I-beams

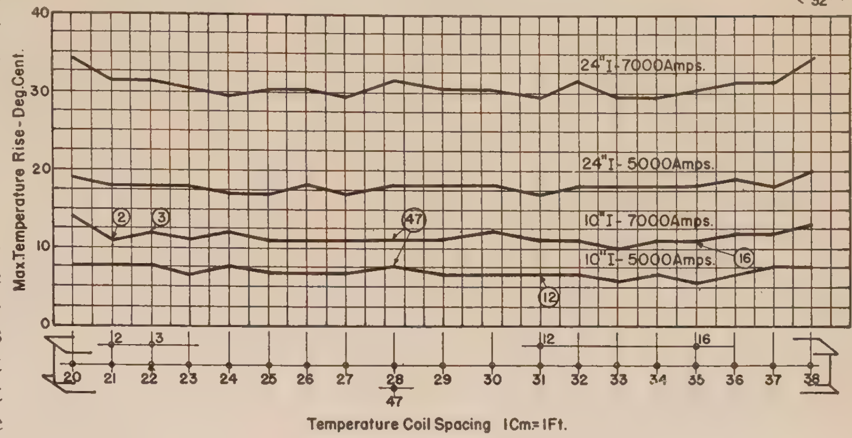
discussions with the engineers of various electrical manufacturers indicated that the information available was so limited in scope and so specific in purpose that it was of little use for the immediate problem.[4] Thus it was obvious that tests held the only promise of a successful solution.

Test Procedure

The idea of tests on the existing structure to determine the remedial measures was immediately abandoned because it was feared that the building might be damaged by overheating. It was further believed that the mass effect (complex thermal behavior) would preclude any understanding of the variables. Laboratory tests had all the desired advantages but there was no assurance that laboratory conclusions could be accurately translated into practical situations. These considerations led to a series of coördinated tests in the laboratory and on the existing structure, since the fundamental work could be done in the laboratory and then cautiously verified on the structure with minimum hazard. The investigation was limited to obtaining only data having a direct application to the construction problems.

Beam Size	Amps.	Avg. Amb't.	Test Specimens		
24"	7000	23.6°		24"-79.9# I	10"-25.4# I
24"	5000	23.1°	Length	20'-0"	20'-0"
10"	7000	17.9°	Section	23.33 □"	7.38 □"
10"	5000	20.3°	Periphery	75"	38"

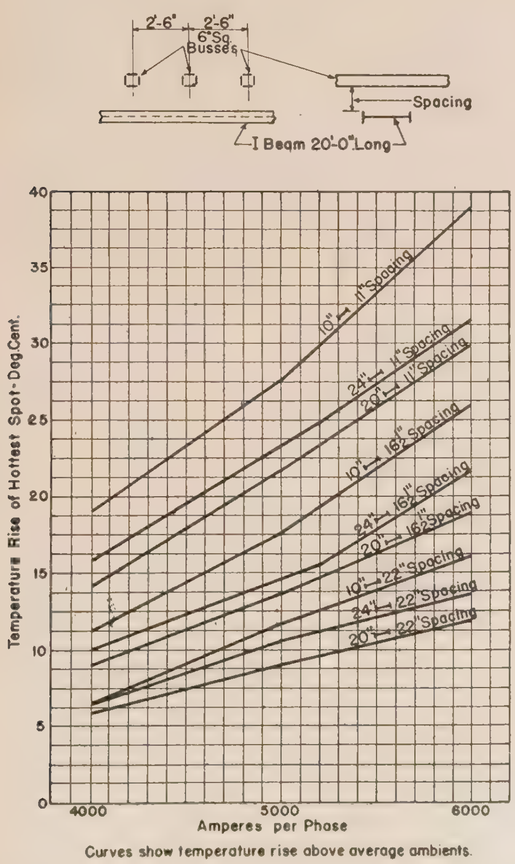




Temperature points are Nos 20 to 38 unless otherwise noted by numbers in circle.
Tests made with beams inside single phase loop.

Fig. 11. Temperature rise in I-beam vs current and beam size

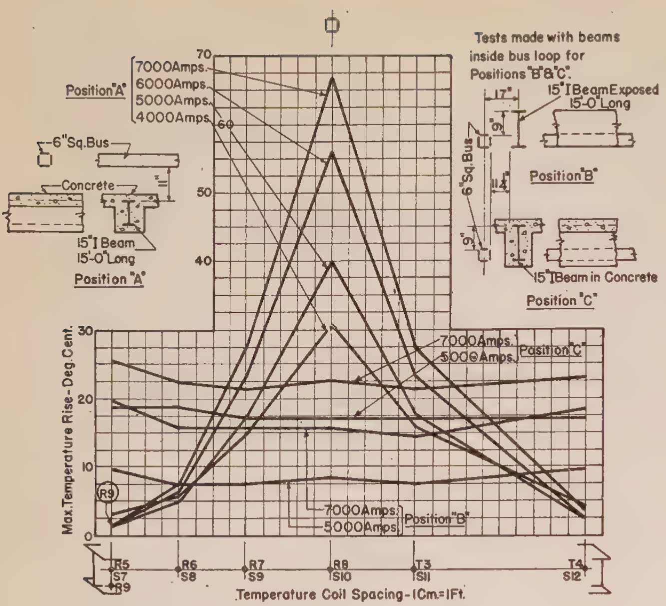
It was clearly impossible to set up any reasonable laboratory test for the determination of the maximum permissible rise. There was a general feeling that there must be some inductive heating in the already operating structure and that, if such heating were excessive, its results would have already been discovered or indicated by cracks in the concrete. One of the generators was selected for a test and thermocouples were embedded in the fireproofing against the structural steel adjacent to the lead runs and bus conductors. The current was held approximately constant at 2,750 amp for 57 hr. The maximum steel temperature recorded during the test was $82^1/_2$ deg C ($180^1/_2$ deg F). Visual inspection showed no evidence of distress of any kind. Therefore 80 deg C (176 deg F) was arbitrarily adopted as the maximum permissible temperature in the steel, since the test current used represented the maximum long time load encountered in previous normal operation and judgment indicated that temperatures of the order encountered should cause no damage. This test clearly demonstrated the danger of attempting to account for the mass effect. One point opposite a dead bus showed a greater rise than a similar point identically located with reference to a live bus.



Curves show temperature rise above average ambients.

Fig. 10. Temperature rise in I-beam vs current, clearance, and beam size

The laboratory tests were made at the Philadelphia Works of the General Electric Company. This work was carried on continuously 24 hr a day for approximately 100 days, with but slight interruption. Tests were made on structural I-beam sections, conduit, conduit loops, cell doors, and ferrous bus support



Position	Amps.	Avg. Conc.Temp.	Avg. Amb't.
A	7000	35.5°	24.4°
	6000	31.8°	22.6°
	5000	31.7°	24.6°
	4000	27.8°	21.8°
B	7000	—	18.3°
	5000	—	20.5°
C	7000	33.4°	22.5°
	5000	33.1°	22.8°

Test Specimen
15"-42.9# I Beam
Length-15'-0"
Section-12.49$^{\square''}$
Periphery-51"

Temperature points are R5 to T4 for concrete unless otherwise noted by number in circle.
Temperature points are S7 to S12 for exposed beam.
Curves show temperature rise above average ambients.

Fig. 12. Temperature rise in I-beam vs current and beam position

fittings. The I-beams used ranged from 10 to 24 in. in depth and from 10 to 24 ft in length. Clearance effects were investigated for spacings from $5^1/_2$ to $27^1/_2$ in. between conductors and ferrous materials. The current values employed ranged from 2,600 to 7,000 amp per phase at 60 cycles for both single-phase loops and 3-phase flat conductor arrangements.

The heating characteristics of I-beam sections, both of carbon and silicon steels, were examined in open air, in heat insulated boxes, and encased in concrete, a composite concrete-steel section having been removed from Richmond Station for this purpose. (Fig. 8.) The heating characteristics of straight and looped conduits were determined, and the characteristics of short-circuited bands and amortisseur grids were observed under many conditions. No tests were made on reënforcing because of the impracticability of such investigation and the belief that there was little likelihood of serious heating because of the small cross section of the bars and the expected high resistance of the joints.

Results of Laboratory Tests

Some seemingly new phenomena and inconsistent data obtained from these tests are as yet unexplained. Figures 3 and 4 illustrate some rather unexpected phenomena for which no satisfactory explanation has been found. Casual consideration would indicate that, with the physical arrangement shown in Fig. 3, there should be 3 points of elevated temperatures, one under each of the 3 buses. This was not the case; there was but one such point and it was always under one of the outside phases. The position of this point for beams in either concrete or open air could be shifted by the reversal of the phase rotation or by the insertion of a copper plate between the bus and the beam but the point was invariably under one of the outside phases. Another case not yet accounted for is shown in Fig. 5, where it is obvious that factors other than the depth of the beam determine the heating.

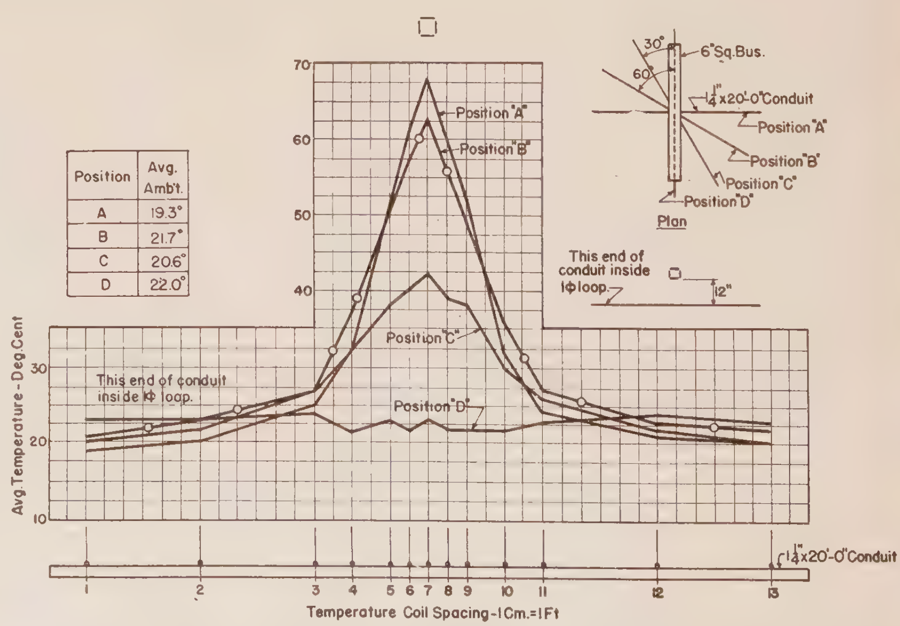
The following deductions can be made from the results of the complete series of laboratory tests:

General Relationships

Carbon vs. Silicon Steel. Any differences which might exist between the magnetic and thermal properties of the carbon and silicon structural steels used were unimportant in so far as this particular problem was concerned. A comparison of the 2 alloys is shown in Fig. 6.

Temperature Rise vs. Current. The temperature rise in I-beams is a direct function of the current for fixed physical relationship. Within the limits of observations (7,000 amp maximum), there is no thermal saturation effect (Fig. 7). Other tests showed that the conclusion is also valid for beams in open air.

Temperature Rise vs. Clearance. The temperature rise in I-beam sections, conduit, and conduit loops is an inverse function of the clearance between the steel and the nearest conductors. The temperature rise for a given current and clearance is materially affected by the shapes and relative positions of conductors and steel members. For example, tests indicated that greater heating occurs with the web of a beam parallel to a 3-phase circuit than with the flange in that position. It is impossible, even in the case of a bare I-beam, to draw a reliable conclusion as to the ultimate temperature for a stated current and clearance unless all of the details are known (Figs. 9 and 5).



Position	Avg. Amb't.
A	19.3°
B	21.7°
C	20.6°
D	22.0°

Fig. 13. Temperature rise in straight conduit vs angular position of conduit

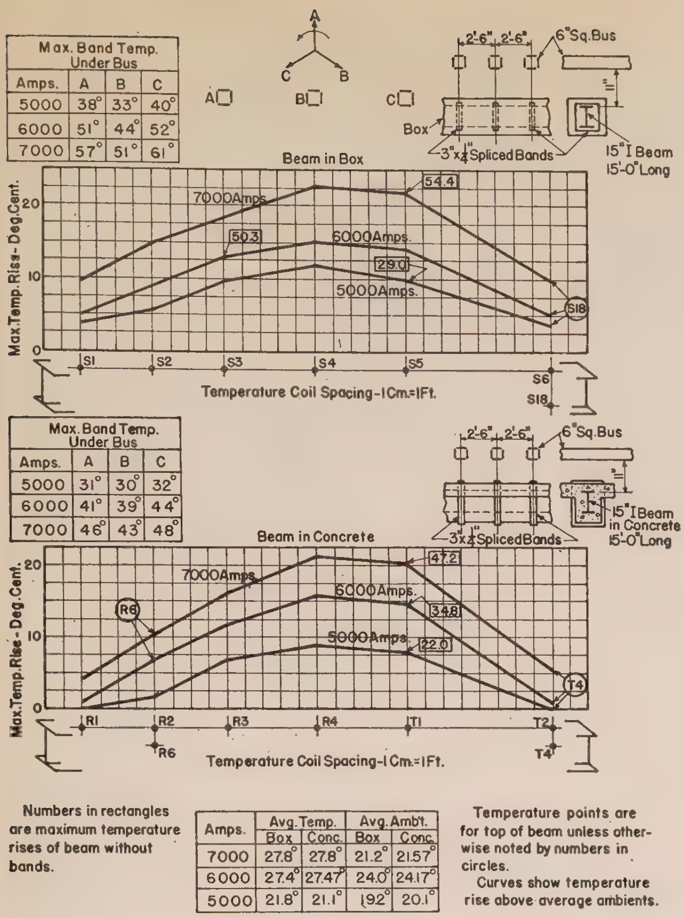


Fig. 14. Temperature rise in I-beam vs current with and without short-circuited bands

Temperature Rise vs. Size of Section. The temperature rise in an I-beam appears to be an inverse function of depth of beam when the beam and conductor axes are at right angles and a direct function when their axes are parallel. These generalizations are based on Figs. 10 and 11. The first is subject to the same comments as made in connection with Fig. 5 and is apparently inconsistent. Conclusions on this relationship should, therefore, be used with caution.

Temperature Rise vs. Axial Relationships. The temperature rise in an I-beam or single straight conduit is a direct function of the angle between the conductor and beam or conduit, being maximum at 90 deg and minimum at 0 deg (Figs. 12 and 13).

Temperature Rises With 1- and 3-Phase Circuits. Single-phase circuits induce greater temperature rises in I-beams, conduits, and conduit loops than 3-phase circuits (Fig. 9).

Protective Devices

Short-Circuited Bands vs. Amortisseur Grids. In cases where buses and I-beams cross at right angles, short-circuited bands are considerably more effective in reducing temperature rises in the beam than amortisseur grids (Figs. 14 and 15). Conversely, when the conductor and beam axes are parallel, the amortisseur grids are most effective. The ineffectiveness of short-circuited bands under this condition seemed so obvious that no confirmatory tests were made.

Short-Circuited Bands With I-Beam at Right Angles to Bus. The effectiveness of short-circuited bands is not greatly altered by the cross section of the band or the length of band circuit, the temperature rise in the steel, within relatively narrow limits, being an inverse function of the gross cross section of the band. The temperature rise of the band follows a reverse reaction and increases rapidly as the band cross section or number of grouped bands is decreased. When a single band is used, the minimum temperature rise in the steel occurs when the band is placed directly opposite the conductor. With multiple bands, the steel temperature is lowest for symmetrical dispositions of bands or groups of bands relative to the point opposite the conductor. Under these conditions the temperature reduction is very pronounced, but it is affected by so many variables that it is probably changed radically for every different section and space relationship between the beam and conductor. Multiple bands, properly placed, are seemingly much more effective than single bands for the same cross section. Woven metal braids applied either as series turns or as multiple paths will produce about the same over-all results as bands of solid metal, provided that the gross cross section is comparable in both cases. The manner of closing the bands, whether bolting or welding, has little influence on the results as long as the resistance of the joints is kept low. As a general statement, bands properly installed can reduce steel temperatures somewhat in excess of 50 per cent (Fig. 16).

Amortisseur Grids. Amortisseur grids placed parallel to conductors are most effective in reducing temperature rises in I-beams and conduit loops which are also parallel to the conductors. They are least effective when beams or single conduits cross the conductors at right angles.

The results attained in all cases, for a given cross section of amortisseur, will depend upon the physical interrelationship between the conductors, the individual amortisseur bars, and the beam or conduit loop. Disproportionate variations in results are produced by relatively slight differences in bar locations. Since the effectiveness of the grid is determined primarily by the number and arrangement of the bars and to a much lesser extent by cross section, it is impossible to draw any conclusion as to the relationship between the steel temperature reduction and the total cross section of the grid. Fortunately, the best results seem to come from a dispersion of grid metal rather than a concentration and this tends toward a minimum grid rise for a given reduction in steel temperature. Amortisseurs can become a partial liability because of their own heat losses. They should only be installed after careful consideration of their contribution to the general ambient temperature as well as the mechanical details providing for expansion and insuring premanent clearances. The prevention of objectional rattles and hum also warrants some thought to the manner of their installation (Figs. 15 and 17).

Copper Plates. Copper plates interposed between the conductors of a 3-phase bus and an I-beam when the conductors are equidistant

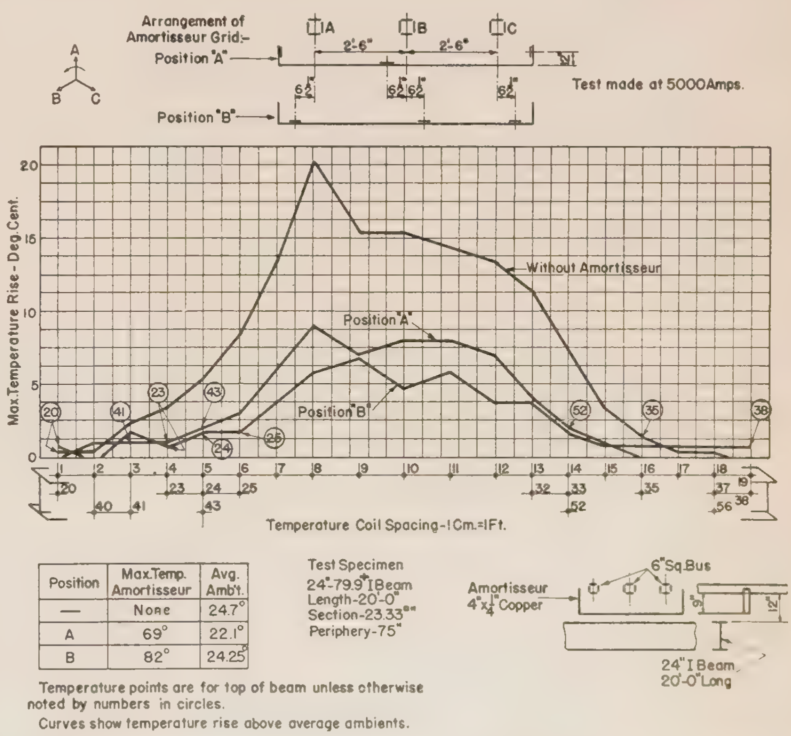
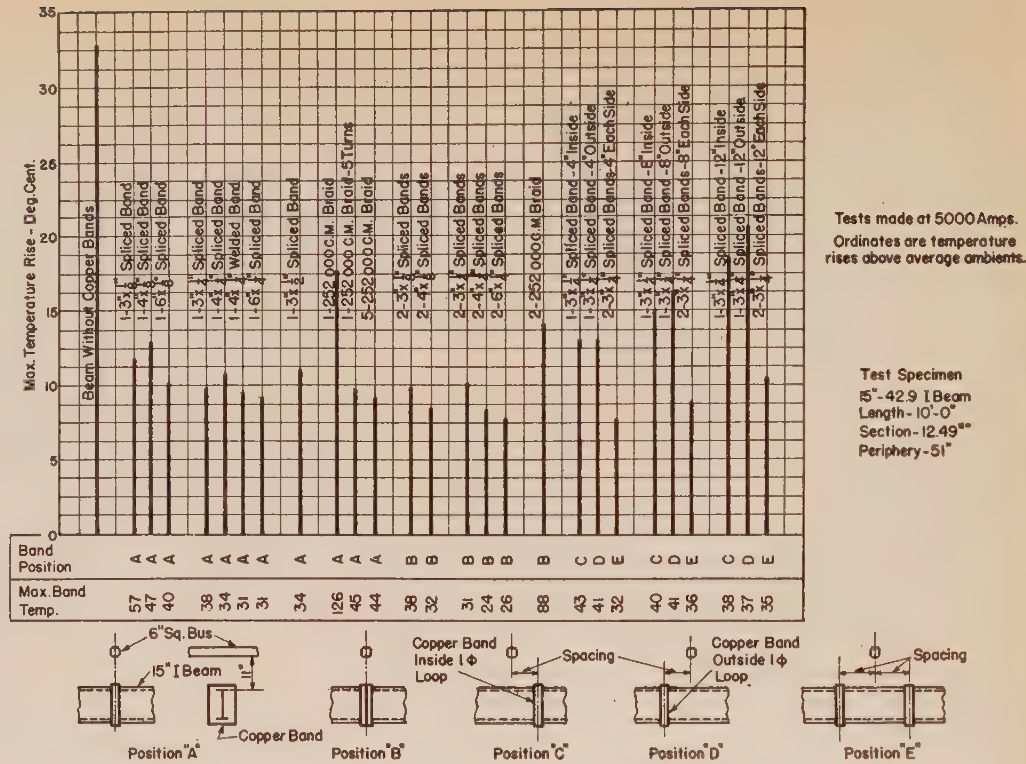


Fig. 15. Temperature rise in I-beam vs position of amortisseur bars

Fig. 16. Temperature rise in I-beam vs number, size, grouping, and position of short-circuited bands



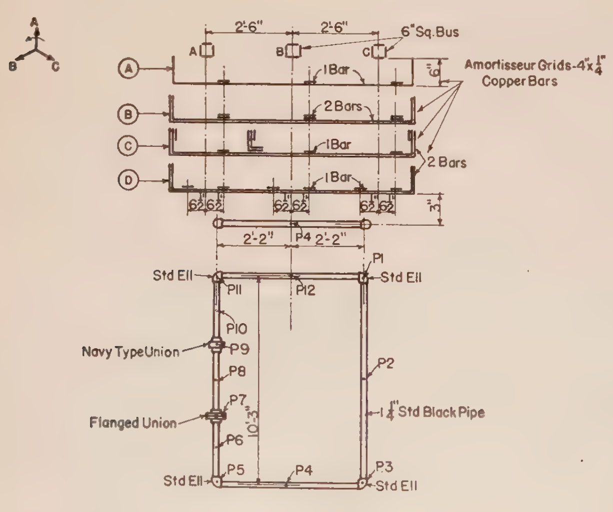
from and at right angles to the beam, are active in reducing the temperature rise in the steel. There is little choice between plates $^1/_{16}$ and $^1/_8$ in. thick, although the operating temperature of the plate is increased considerably for the thinner section (Fig. 4). No single-phase tests were made with plates because they appeared to be less effective than bands and amortisseurs.

Practical Observations

Conduit Loops. The current carrying capacity of conductors in conduits can be materially decreased and the conductor placed in jeopardy by inductive heating in the conduit. The most pronounced danger zones occur where conduits cross high current conductors at angles approaching 90 deg. At such points local heating due to eddy currents and hysteresis may be superimposed on losses resulting from circulating currents originating in other elements of the conduit system. The greatest hazard from circulating currents appears to arise from high resistance joints in the conduit where conduit loops parallel inducing conductors. The hazard is a function of the length of the parallel. It was accidently demonstrated in the laboratory that a single-phase bus carrying 7,000 amp and crossing a flat conduit network at a distance of about 24 in. could produce sufficient circulating current to burn through a $1^1/_2$-in. conduit at its junction with a box.

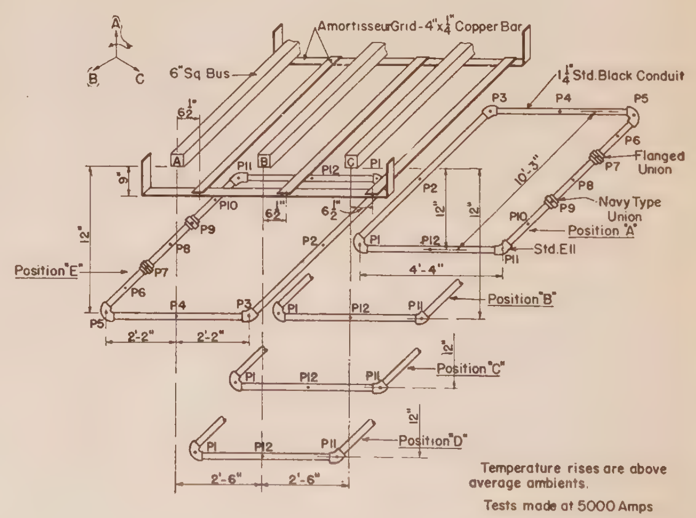
In the design of conduit systems to be installed in the vicinity of heavily loaded conductors, it is advisable to maintain as much clearance as possible between conduits and conductors, to cross the conductors with conduits as obliquely as possible, and to maintain the electrical resistance of conduit circuits as low as reasonably feasible.

The order of the temperatures which may be expected in conduit loops, exclusive of excessive temperatures at high resistance joints,



Arrg't. of Amort.	Avg. Amb't.	Max. Amort. Temp.	Temperature Rise - Degrees Centigrade											
			P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
None	20.4°	None	27.6°	23.6°	26.6°	33.6°	13.6°	16.6°	21.6°	20.6°	15.6°	20.6°	24.6°	33.6°
A	20.1°	68°	6.9°	5.9°	5.9°	10.9°	6.9°	3.9°	2.9°	2.9°	2.9°	3.9°	7.9°	11.9°
B	21.2°	57°	8.8°	5.8°	9.8°	12.8°	6.8°	5.8°	3.8°	4.8°	5.8°	5.8°	5.8°	10.8°
C	23.5°	59°	5.5°	2.5°	6.5°	7.5°	4.5°	3.5°	2.5°	2.5°	3.5°	3.5°	3.5°	8.5°
D	21.5°	56°	1.5°	2.5°	2.5°	4.5°	3.5°	3.5°	2.5°	2.5°	2.5°	2.5°	2.5°	4.5°

Fig. 17. Temperature rise in conduit loop vs position of amortisseur bars



Position of Loop	Avg. Amb't.	Max. Amort. Temp.	Temperature Rise – Degrees Centigrade											
			P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
A	22.2°	None	12.8°	2.8°	12.8°	5.8°	1.8°	0.8°	0.8°	0.8°	0.8°	1.8°	1.8°	5.8°
A	21.3°	75.0°	1.7°	1.7°	1.7°	0.7°	0.7°	-0.3°	-0.3°	-0.3°	0.7°	-0.3°	0.7°	0.7°
B	21.7°	None	12.3°	6.3°	11.3°	22.3°	7.3°	3.3°	3.3°	3.3°	2.3°	4.3°	7.3°	24.3°
B	20.1°	67.0°	2.9°	2.9°	2.9°	7.9°	1.9°	0.9°	-0.1°	-0.1°	0.9°	0.9°	1.9°	7.9°
C	20.7°	None	21.3°	14.3°	21.3°	20.3°	20.3°	12.3°	11.3°	11.3°	8.3°	17.3°	21.3°	21.3°
C	19.7°	70.0°	9.3°	3.3°	8.3°	7.3°	4.3°	2.3°	1.3°	1.3°	1.3°	2.3°	4.3°	7.3°
D	20.4°	None	27.6°	23.6°	26.6°	33.6°	13.6°	16.6°	21.6°	20.6°	15.6°	20.6°	24.6°	33.6°
D	20.1°	68.0°	6.9°	5.9°	5.9°	10.9°	6.9°	3.9°	2.9°	2.9°	2.9°	3.9°	7.9°	11.9°
E	22.5°	None	8.5°	4.5°	7.5°	27.5°	8.5°	4.5°	2.5°	4.5°	4.5°	4.5°	6.5°	29.5°
E	23.5°	83.0°	8.5°	3.5°	7.5°	13.5°	6.5°	3.5°	2.5°	4.5°	3.5°	3.5°	6.5°	13.5°

Fig. 18. Temperature rise in conduit loop, with and without amortisseur vs position of loop

Table III—Temperatures in Building Steel Before and After Installation of Bands and Amortisseurs

Size of Beam	Bands and Amortisseurs Installed	Clearance in Inches	Amperes Per Phase	Temperature Deg C
40 in. I	No	11	2750	*82.5
	Yes	10 3/4	4830	*27.0
40 in. I	No	9	2750	58.0
	Yes	4 7/8	4830	44.0
40 in. I	No	9	2750	71.0
	Yes	4 7/8	4830	45.5
18 in. I	No	9	2750	74.0
	Yes	5 3/8	4540	51.5
14 x 12 in. H	No	26	2750	42.0
	Yes	25 1/2	4670	**42.5
14 x 12 in. H	No	26	2750	54.5
	Yes	25 1/2	4830	**49.0
12 x 10 in. H	No	27	2750	46.5
	Yes	26 1/2	4670	**61.5

* The points corresponding to these temperatures were similarly located with reference to both bus and structure but the first was within the influence of a reactor, while the second was not. This accounts for the wide difference of temperature.

** The bands associated with these readings were not properly located due to structural obstruction. Proper location would probably produce a marked decrease in temperature.

is indicated by Fig. 18. This figure also gives an idea of what may be accomplished by the use of amortisseurs.

Cell Doors. Results of tests on sheet steel and steel frame doors indicate that objectionable magnetic heating may be expected in the metal parts when located in proximity to conductors carrying currents in excess of 3,000 amp. When the position or construction of the doors provides a metallic loop or circuit unsymmetrical with the conductor, there will be additional heating resulting from circulating currents. This occurs whether the metal is magnetic or not.

Bus Clamps. Bus clamps having ferrous parts will not show excessive temperature elevations when used on conductors carrying up to 7,000 amp, provided that a loop of magnetic material is not formed around the conductor.

In order to determine the efficacy of the protective measures, a second test was made after all bands and amortisseur networks had been installed. The test current was applied to only a short section of the run initially in order to observe reactions. This trial test being satisfactory, an average current of 4,680 amp was maintained for approximately 84 hr to bring the structure to stable temperature, which was then held for approximately 8 hr.

It was possible to locate many thermocouples for this test in the same physical relationship to the steel structure and the conductor as in the earlier structure test, so it was possible to obtain an index of the effectiveness of the bands and grids. (Table III) The 2 tests were conducted under practically the same weather conditions.

This test clearly demonstrated the justification for the laboratory tests. The amortisseur grids had been installed in advance of final laboratory information in order to meet the demands of construction schedules. The data showed that the single bar grid as installed could be expected to heat excessively and this was confirmed in the test. It was found necessary to reënforce the single bar section with an additional bar throughout.

The losses in the amortisseur grids materially increase the amount of heat liberated in the conductor enclosures. This added confirmation to previous indications that forced ventilation would be required.

During the test, excessive heating was observed in the metal framework of the lead run compartments

Fig. 20. Single-phase test on single conduit and conduit loop

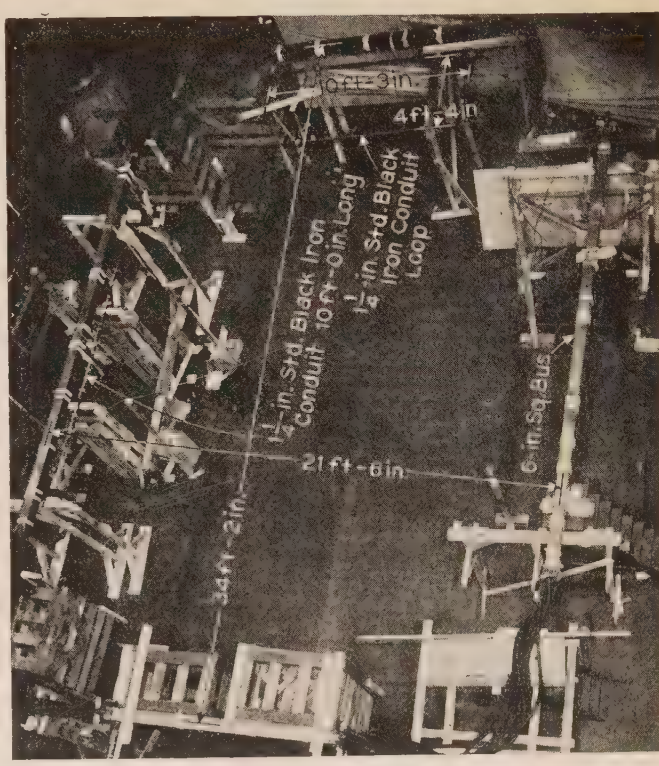
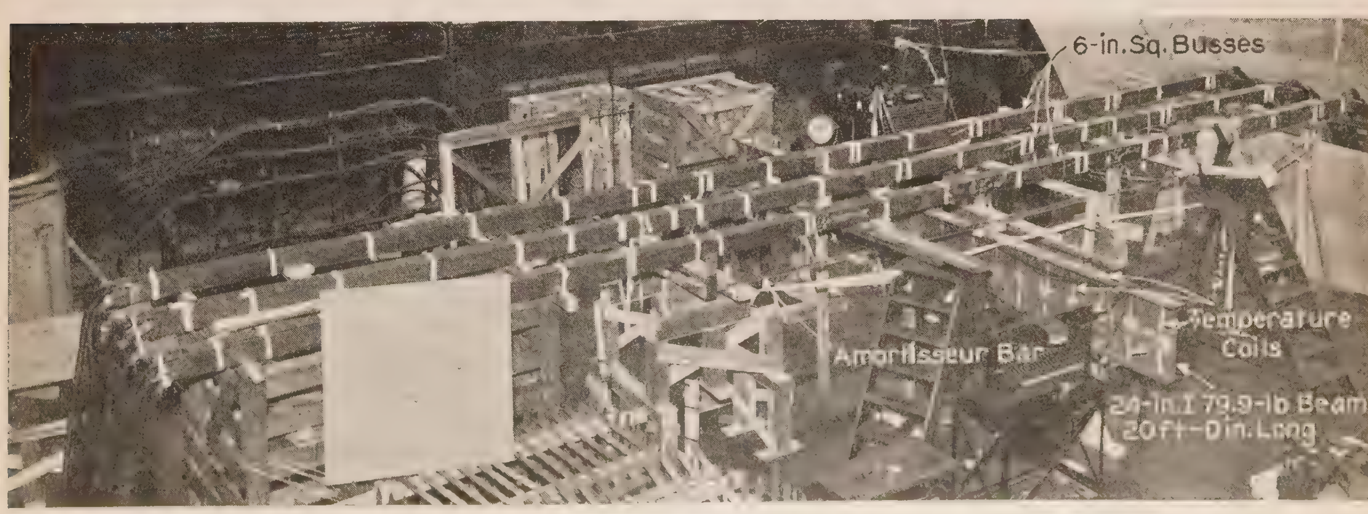


Fig. 19. 3-phase test on I-beam with amortisseur



from loops formed by multiple ground connections. In some instances the circulating currents produced points of incandescence at high resistance joints in the metal framework. Heating was substantially reduced by removing from each section all grounds except one and opening the metallic circuit of the ironwork at intervals to prevent forming of loops.

No attempt was made to measure temperatures in conduit and in reënforcing steel due to their inaccessibility. However, all parts of the building were carefully examined by hand for elevated temperatures, but none were found, so it was assumed that the protective devices were functioning successfully.

Valuable advice and coöperation from Messrs. D. C. Prince, R. M. Spurck, and C. E. Merris of the General Electric Company, and Messrs. H. W. Papst and L. A. Kilgore of the Westinghouse Electric & Manufacturing Company are gratefully acknowledged.

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Cross Current of a 5-Arm Network

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This paper treats the loci of cross currents in 5-arm networks with constant coefficients at constant applied voltage. It is shown that at constant frequency of applied voltage, the locus of the cross current is a circle when any one of the network arms is varied at constant phase angle or along one of its components. When the network arms are fixed and the frequency is varied, the locus of the cross current is the sum of several circles, the number depending upon how many of the impedance arms vary with frequency. The general 5-arm network is treated analytically and the application of the method in determining the loci is illustrated by a typical network for which the cross current is evaluated for constant and for varying frequency.

THE study of circuits consisting of 4 impedances arranged in conventional bridge form, involves, in general, 1 of the 2 following considerations:

1. Variation of the cross potential difference appearing across the midpoints of the network.
2. Variation of the cross current which would flow through an impedance connected across the midpoints of the network.

When such a network is employed in conjunction with a device which draws no current, or a negligible amount, the variation of cross potential difference is sufficient to determine the performance of the circuit. Such is the case with bridge measuring or control networks where the detector arm consists of a properly biased tube circuit. The variation of cross potential difference has been treated in a previous paper (see "Cross Potential of a 4-Arm Network," by A. C. Seletzky, Elec. Engg., v. 52, 1933, p. 861–7) where it was shown that the locus of the cross potential difference is:

1. A circle when the network is operated at constant applied voltage at constant frequency and any one of its arms is varied at constant phase angle or along one of its components.
2. The sum of several circles when the arms remain fixed and the frequency of the applied voltage is varied.

If a current drawing instrument such as a transformer or galvanometer is placed across the midpoints of the network, the problem becomes the determination of the locus of the cross current which flows through this additional impedance. It is the purpose of the present paper to treat this condition for both fixed and varying frequencies. To facilitate comparison between the determination of the loci for cross potential difference and cross current, the same network and constants will be used in this paper as in the preceding one.

Full text of a paper recommended for publication by the A.I.E.E. committee on instruments and measurements, and scheduled for discussion at the A.I.E.E. summer convention, Hot Springs, Va., June 25–29, 1934. Manuscript submitted Jan. 25, 1934; released for publication March 12, 1934. *Not published in pamphlet form.*

General 5-Arm Network

In Fig. 1 is shown a general 5-arm impedance network having impedances Z_a, Z_b, Z_c, Z_d, and Z_g, with constant applied voltage E at constant frequency. The current I_g flowing through the cross impedance Z_g is

$$I_g = \frac{E(Z_bZ_c - Z_aZ_d)}{Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + Z_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)]} \quad (1)$$

If I_g is the current in amperes per volt of applied voltage, then

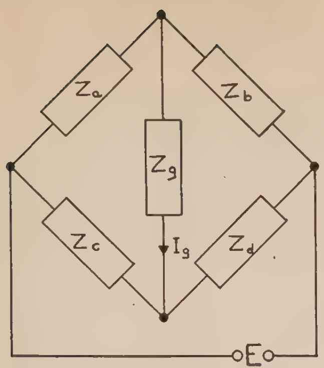

Fig. 1. General 5-arm network

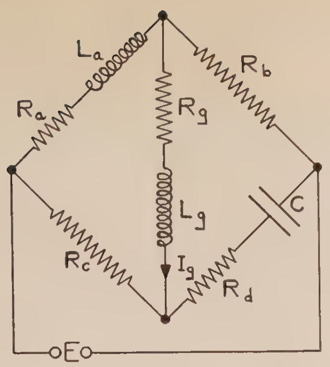

Fig. 2. Network used for example

$$I'_g = \frac{I_g}{E} = \frac{Z_bZ_c - Z_aZ_d}{Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + Z_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)]} \tag{2}$$

To treat the loci of the cross current under various conditions, the equation of a circle in the form of a linear fractional transformation as given by Schenckel (see "Geometrische Oerter an Wechselstromdiagrammen," by M. Schenckel, *E. T. Z.*, v. 22, 1901, p. 1043–4) will be taken as the canonical form. This is

$$S = \frac{\alpha + \beta\rho}{\gamma + \delta\rho} \tag{3}$$

Here S is a vector describing a circle as the scalar variable ρ ranges from minus to plus infinity and α, β, γ, and δ are constants. Methods of determining the circle from these constants and of drawing a scale line have been described in the previously mentioned paper by one of the present authors (Elec. Engg., v. 52, 1933, p. 861–7). This scale line is any line drawn perpendicular to the line joining the center of the circle with the point on the circle corresponding to $\rho = \infty$. Lines drawn from the latter point to any other points on the circle such as those corresponding to $\rho = 0$ and $\rho = 1$ fix the scale on the scale line. This scale is then extended linearly along the scale line. In the problems which follow, the circles will be determined by evaluating S at 3 points, corresponding to ρ equal to zero, infinity, and some convenient third point. These points will also be sufficient to determine the scale line.

Five-Arm Network at Constant Frequency

A number of conditions which at constant frequency of applied voltage give rise to circular loci for the cross current will now be studied.

When one of the network arms, as Z_d, is varied at constant phase angle, this arm may be written as $Z_d = Z'_d\rho$, where Z'_d is a unit vector having the phase angle of Z_d and ρ is the scalar variable. Substituting this form into eq 2 gives eq 4.

Equation 4 is in the form of a circle, since from eq 3, S becomes I'_g and the constants are as given in eq 5.

In the same manner, if the resistance component of one of the arms, as Z_d, is varied, then $Z_d = R_d + jX_d$ is substituted into eq 2 giving eq 6.

Equation 6 is likewise in circular form having the constants given in eq 7.

When the quadrature component of one of the arms, as Z_d, varies, the same substitution is performed as for a variable resistance component and the terms are arranged as given in eq 8. This is a circle having the constants given in eq 9.

Thus eqs 4, 6, and 8 demonstrate that with constant applied voltage at constant frequency, the locus of cross current is a circle when any one of the network arms varies at constant phase angle or along one of its components. In this respect the behavior of cross current is precisely the same as that of cross potential difference. That there is no further complication at constant frequency in the form of eq 2 for cross current as compared to the equation for cross potential difference is due to the fact that the addition of the fifth arm, Z_g, introduces additional terms in the denominator only, and in such a way that the equation for cross current may always be written to conform to the circular form of eq 3.

As a practical example of the use of the equations just derived, the same resistance, inductance, and capacitance network used in the previous paper to illustrate the locus of cross potential difference will

$$I'_g = \frac{Z_bZ_c - Z_aZ_d'\rho}{Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + [Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)]Z_d'\rho} \tag{4}$$

$$\left.\begin{aligned} \alpha &= Z_bZ_c & \gamma &= Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] \\ \beta &= -Z_aZ_d' & \delta &= [Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)]Z'_d \end{aligned}\right\} \tag{5}$$

$$Ig' = \frac{Z_bZ_c - jZ_aX_d - Z_aR_d}{Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + jX_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)] + R_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)]} \tag{6}$$

$$\left.\begin{aligned} \alpha &= Z_bZ_c - jX_dZ_a \\ \beta &= -Z_a \\ \gamma &= Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + jX_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)] \\ \delta &= Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c) \\ \rho &= Rd \end{aligned}\right\} \tag{7}$$

$$I'_g = \frac{Z_bZ_c - Z_aR_d - jZ_aX_d}{Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + R_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)] + j[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)]X_d} \tag{8}$$

$$\left.\begin{aligned} \alpha &= Z_bZ_c - Z_aR_d \\ \beta &= -jZ_a \\ \gamma &= Z_c[Z_aZ_g + Z_bZ_g + Z_aZ_b] + R_d[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)] \\ \delta &= j[Z_a(Z_g + Z_c) + Z_b(Z_g + Z_a + Z_c)] \\ \rho &= Xd \end{aligned}\right\} \tag{9}$$

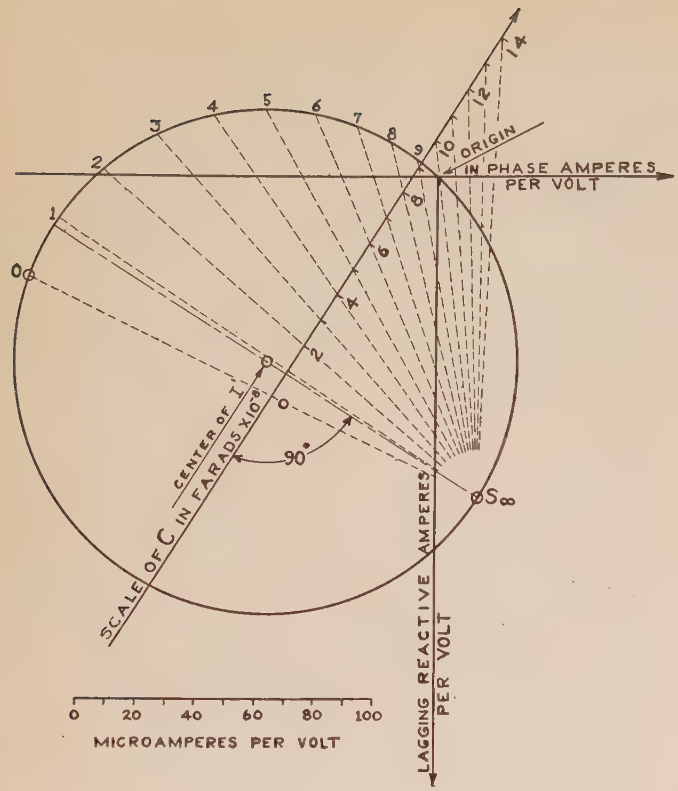

Fig. 3. Locus of cross current

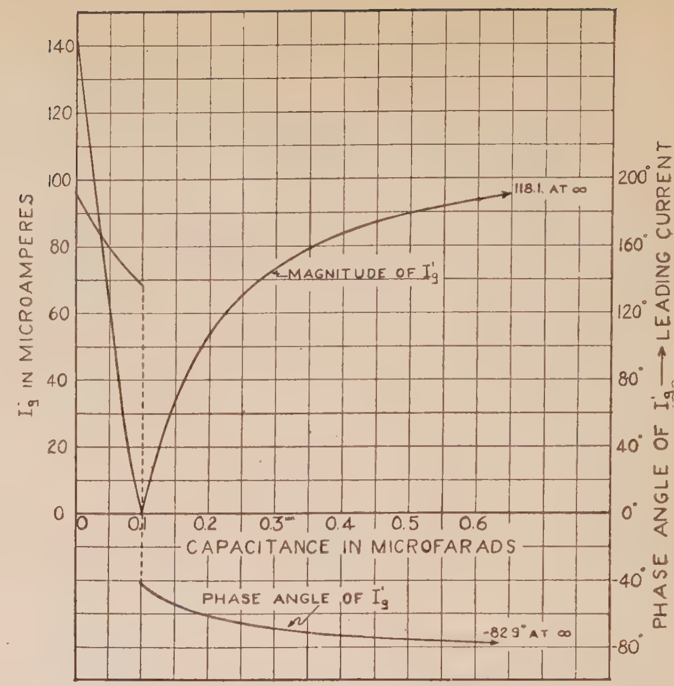

Fig. 4. Variations of cross current as a function of capacitance

be employed, with the addition of the cross arm Z_g, which will be considered to be inductive. This network is shown in Fig. 2. As before, the fixed arms will be taken as Z_a, Z_b, Z_c, and the capacitance C in the arm Z_d will be varied from zero to infinity. The constants of this network are:

$$Z_a = R_a + j\omega L_a$$

$$Z_b = R_b$$

$$Z_c = R_c$$

$$Z_d = R_d - \frac{j}{\omega C}$$

$$Z_g = R_g + j\omega L_g$$

Inserting these constants in eq 2 for cross current:

$$I'_g = \frac{R_bR_c - (R_a + j\omega L_a)\left(R_d - \dfrac{j}{\omega C}\right)}{R_c[(R_a + j\omega L_a)(R_g + j\omega L_g) + R_b(R_g + j\omega L_g) + R_b(R_a + j\omega L_a)] + \left(R_d - \dfrac{j}{\omega C}\right)[(R_a + j\omega L_a)(R_g + R_c + j\omega L_g) + R_b(R_g + j\omega L_g + R_a + R_c + j\omega L_a)]} \quad (10)$$

Since C is now the scalar variable representing ρ in the linear fractional transformation equation, the above expression for cross current must be rewritten in an appropriate circular form with C as a factor of a single term in the numerator and denominator. Rearranging the terms in eq 10 accordingly:

$$I'_g = \frac{j(R_a + j\omega L_a) + \omega[R_bR_c - R_d(R_a + j\omega L_a)]C}{-j\{(R_a + j\omega L_a)(R_g + R_c + j\omega L_g) + R_b[R_g + R_a + R_c + j\omega(L_a + L_g)]\} + C\{\omega R_c[(R_g + j\omega L_g)(R_b + R_a + j\omega L_a) + R_b(R_a + j\omega L_a)] + \omega R_d[(R_a + j\omega L_a)(R_c + R_g + j\omega L_g) + R_b(R_g + R_a + R_c + j\omega[L_a + L_g])]\}} \quad (11)$$

The constants for the circular locus of cross current above are:

$$\left.\begin{aligned}
\alpha &= j(R_a + j\omega L_a) \\
\beta &= \omega[R_bR_c - R_d(R_a + j\omega L_a)] \\
\gamma &= -j\{(R_a + j\omega L_a)(R_g + j\omega L_g + R_c) + R_b[R_g + R_a + R_c + j\omega(L_a + L_g)]\} \\
\delta &= \omega R_c[(R_g + j\omega L_g)(R_b + R_a + j\omega L_a) + R_b(R_a + j\omega L_a)] + \omega R_d\{(R_a + j\omega L_a)(R_g + R_c + j\omega L_g) + R_b(R_g + R_a + R_c + j\omega[L_a + L_g])\} \\
\rho &= C
\end{aligned}\right\} \quad (12)$$

Obtaining the position of the critical points necessary to determine the circle, for $C = \infty$

$$(I'_g)_\infty = \frac{R_bR_c - R_d(R_a + j\omega L_a)}{R_c[(R_g + j\omega L_g)(R_b + R_a + j\omega L_a) + R_b(R_a + j\omega L_a)] + R_d[(R_a + j\omega L_a)(R_g + R_c + j\omega L_g) + R_b(R_g + R_a + R_c + j\omega[L_a + L_g])}$$

for $C = 0$, $\quad (I'_g)_0 = \dfrac{-(R_a + j\omega L_a)}{(R_a + j\omega L_a)(R_g + R_c + j\omega L_g) + R_b[R_g + R_a + R_c + j\omega(L_a + L_g)]}$

Referring to the foregoing paper, eq 20, it will be noticed that when

$$R_d = \frac{R_a R_b R_c}{R_a^2 + \omega^2 L_a^2} = R'_d$$

$$C = \frac{R_a^2 + \omega^2 L_a^2}{R_b R_c \omega^2 L_a} = C'$$

the cross potential difference is zero. Thus for these values the cross current will also be zero. If $R_d = R'_d$, a convenient value for C to determine the third point on the circle is then C'. If this is not the case, some other value of C must be taken and the corresponding value of I'_g computed. With these 3 points the circle is completely determined together with its scale line.

Numerical Example

To illustrate this problem numerically, the same values of impedance will be employed in the network arms, namely:

R_a = 1,130 ohms

L_a = 0.2870 henries

$R_b = R_c$ = 2,000 ohms

R_d = 1,000 ohms

$-\infty < C < +\infty$

If the network be operated at 1,000 cycles, the values of R'_d and C' for null cross current are 1,000 ohms and 10^{-7} farads, respectively. The value of R_d is fixed at 1,000 ohms; hence there will be zero cross current for $C = 10^{-7}$ farads. For the cross impedance arm, let the following constants be assumed:

R_g = 1,000 ohms

L_g = 0.0742 henries

Substituting these constants in the expressions for α, β, γ, and δ as given by eqs 12:

$\alpha = (-1.803 + j1.130)10^3$

$\beta = (18.03 - j11.33)10^9$

$\gamma = (10.48 - j10.81)10^6$

$\delta = (125.1 + j152.1)10^{12}$

The cross current of eq 11 may then be represented by:

$$I'_g = \frac{(-1.803 + j1.130)10^3 + (18.03 - j11.33)10^9 \times C}{(10.48 - j10.81)10^6 + (125.1 + j152.1)10^{12} \times C} \quad (13)$$

The critical points necessary to determine the circle and its scale line are:

for $C = 0$

$$(I'_g)_0 = \frac{(-1.803 + j1.130)10^3}{(10.48 - j10.81)10^6} = (-137.3 - j33.78)10^{-6}$$

for $C = \infty$

$$(I'_g)_\infty = \frac{(18.03 - j11.33)10^9}{(125.1 + j152.1)10^{12}} = (13.71 - j107.3)10^{-6}$$

for $C = C' = 10^{-7}$ farads

$I'_g = 0$

The locus of I'_g is shown in Fig. 3. The points $I'_g = 0$ for $C = 10^{-7}$ farads and $(I'_g)_0$ for $C = 0$ determine the linear scale of C on the scale line as indicated. The value of cross current for any value of C may now be read directly on Fig. 3. The variation of the phase angle and magnitude of I'_g as a function of the capacitance is plotted in Fig. 4. It is interesting to compare this plot with the one drawn for cross potential and note the similarity in the shapes of the curves.

Thus any type of 5-arm network with constant coefficients, in which one arm varies at constant phase angle or along one of its components, may be treated exactly as in the foregoing example.

Five-Arm Networks at Varying Frequency

As compared to the locus of cross potential difference for a 4-arm network, the expression for cross current in the fifth impedance element connected across the midpoints assumes a more complicated form, when the network arms remain fixed and the frequency of the applied voltage is varied. This, as may be seen from eq 2, is due to the presence of the impedance of the fifth arm in the denominator, especially when, as is usually the case, this impedance varies with frequency.

The method of determining the locus of cross current when the frequency is varied, is the same as was employed for the cross potential difference. Using the fundamental equation for cross current, eq 2, the constants of the particular network are substituted in it; the terms of the numerator and denominator are then arranged in descending powers of the angular velocity ω and this expression may then be resolved into a sum of several linear fractional transformations. Each of these linear fractional transformations has a circle for its locus and the resultant locus of cross current is obtained by adding corresponding points on the several circles.

The most complicated case involving a 5-arm network at varying frequency is the one in which each arm contains resistance, inductance, and capacitance. If the form $Z_k = R_k + j\omega L_k - \frac{j}{\omega C_k}$ be substituted in eq 2 and the terms arranged in descending powers of ω, then eq 2 will assume the following form:

$$I^1_g = \frac{A_5\omega^5 + A_4\omega^4 + A_3\omega^3 + A_2\omega^2 + A_1\omega + A_0}{B_6\omega^6 + B_5\omega^5 + B_4\omega^4 + B_3\omega^3 + B_2\omega^2 + B_1\omega + B_0} \quad (14)$$

in which $A_0 \ldots\ldots A_5$ and $B_0 \ldots\ldots B_6$ are constants free of ω, involving the resistance, inductance, and capacitance of the network arms only. To evaluate I'_g in eq 14, the denominator is equated to zero and then solved as an equation in ω for the 6 roots $\omega_1 \ldots\ldots \omega_6$. Rewriting eq 14 as the sum of 6 linear fractional transformations:

$$I'_g = \frac{A_5\omega^5 + A_4\omega^4 + A_3\omega^3 + A_2\omega^2 + A_1\omega + A_0}{B_6\omega^6 + B_5\omega^5 + B_4\omega^4 + B_3\omega^3 + B_2\omega^2 + B_1\omega + B_0} =$$

$$\frac{M_1}{\omega - \omega_1} + \frac{M_2}{\omega - \omega_2} + \frac{M_3}{\omega - \omega_3} + \frac{M_4}{\omega - \omega_4} + \frac{M_5}{\omega - \omega_5} + \frac{M_6}{\omega - \omega_6} \quad (15)$$

Equating coefficients of like powers of ω, the M's may be evaluated in terms of the A's and B's and the roots $\omega_1 \ldots \omega_6$ or in terms of A's and B's only since $\omega_1 \ldots \omega_6$ may be expressed in terms of the B's alone. The denominator occurring to the sixth degree, the solution for the 6 roots and for the M's from the 6 resulting simultaneous equations makes the computations rather involved. However, this is the most general case encountered; in practice the networks are generally such that the cross current may be expressed by 2 or more linear fractional transformations, the maximum number of transformations necessary usually being 3 or 4.

As an example of this type of problem, the network used to illustrate the constant frequency problem in Fig. 2 will suffice. Rearranging eq 10 in descending powers of ω the cross current becomes:

$$I'_g = \frac{\frac{1}{L_g(R_c + R_d)}\left[jR_d\omega^2 - \frac{\omega}{L_a}\left(R_bR_c - R_aR_d - \frac{L_a}{C}\right) - \frac{jR_a}{L_aC}\right]}{D} \quad (16)$$

in which the denominator D is:

$$D = \omega^3 - \frac{\omega^2 j}{L_aL_gC(R_c + R_d)}\{CL_g(R_a + R_b)(R_c + R_d) + CL_a[(R_g + R_b)(R_c + R_d) + R_cR_d] + L_aL_g\} - \frac{\omega}{L_aL_gC(R_c + R_d)}\{C[(R_aR_g + R_bR_g + R_aR_b)(R_c + R_d) + R_dR_c(R_a + R_b)] + L_a(R_g + R_c + R_b) + L_g(R_a + R_b)\} + \frac{j}{L_aL_gC(R_c + R_d)}[(R_a + R_b)(R_c + R_g) + R_aR_b] \quad (17)$$

Equating the denominator to zero and solving for ω, 3 roots are obtained, ω_1, ω_2, and ω_3. The cross current may then be written:

$$I'_g = \frac{\frac{1}{L_g(R_c + R_d)}\left[jR_d\omega^2 - \frac{\omega}{L_a}\left(R_bR_c - R_aR_d - \frac{L_a}{C}\right) - \frac{jR_a}{L_aC}\right]}{D} = \frac{M_1}{\omega - \omega_1} + \frac{M_2}{\omega - \omega_2} + \frac{M_3}{\omega - \omega_3} \quad (18)$$

Here M_1, M_2, and M_3 are coefficients free of the variable ω and involving impedance components and ω_1, ω_2, and ω_3 only. Thus the cross current is seen to be composed of 3 circles:

$$S_1 = \frac{M_1}{\omega - \omega_1}; \quad S_2 = \frac{M_2}{\omega - \omega_2}; \quad S_3 = \frac{M_3}{\omega - \omega_3}$$

that is:

$$I'_g = S_1 + S_2 + S_3 \quad (19)$$

These 3 circles may now be plotted together with their respective scale lines of frequency; corresponding vectors on each circle are then added producing the resultant locus of I'_g.

The computations involved in a problem of this type will be given for the network just discussed using the same constants as before with the exception that the capacitance will be maintained at 10^{-7} farads, which value renders the cross current zero at 1,000 cycles. Substituting these constants into eq 16, the expression for cross current becomes:

$$I'_g = \frac{j4.492\omega^2 - j1.769 \times 10^8}{\omega^3 - j6.364 \times 10^4\omega^2 - 6.121 \times 10^8\omega + j1.824 \times 10^{12}} \quad (20)$$

Solving the denominator as a cubic in ω, the roots are:

$$\omega_1 = j5.268 \times 10^4$$
$$\omega_2 = (0.2140 + j0.5481)10^4$$
$$\omega_3 = (-0.2140 + j0.5481)10^4$$

The cross current is now written as the sum of 3 linear fractional transformations:

$$\frac{j4.492\omega^2 - j1.769 \times 10^8}{\omega^3 - j6.364 \times 10^4\omega^2 - 6.121 \times 10^8\omega + j1.824 \times 10^{12}} = \frac{M_1}{\omega - \omega_1} + \frac{M_2}{\omega - \omega_2} + \frac{M_3}{\omega - \omega_3}$$

Thus, since the roots ω_1, ω_2, and ω_3 have just been evaluated, M_1, M_2, and M_3 may be found to have the following values, by equating coefficients of like powers of ω in the above equation:

$$M_1 = j5.664$$
$$M_2 = 1.415 - j0.5857$$
$$M_3 = -1.415 - j0.5857$$

Thus the locus of cross current is composed of 3 circles, S_1, S_2, and S_3 as given in eq 19, in which

$$\left.\begin{aligned} S_1 &= \frac{M_1}{\omega - \omega_1} = \frac{j5.664}{\omega - j5.268 \times 10^4} \\ S_2 &= \frac{M_2}{\omega - \omega_2} = \frac{1.415 - j0.5857}{\omega - (0.2140 + j0.5481)10^4} \\ S_3 &= \frac{M_3}{\omega - \omega_3} = \frac{-1.415 - j0.5857}{\omega - (-0.2140 + j0.5481)10^4} \end{aligned}\right\} \quad (21)$$

To locate the 3 circles, values of ω equal to 0, ∞, and $2\pi \times 1{,}000$ are substituted in the above expressions giving:

for $\omega = 0$

$$S_1 = -0.1075 \times 10^{-3}$$
$$S_2 = (0.005258 + j0.2603)10^{-3}$$
$$S_3 = (0.005258 - j0.2603)10^{-3}$$

for $\omega = 2\pi \times 1{,}000$

$$S_1 = (-0.1060 + j0.0126)10^{-3}$$
$$S_2 = (0.1922 + j0.1129)10^{-3}$$
$$S_3 = (-0.0863 - j0.1257)10^{-3}$$

for $\omega = \infty$

$$S_1 = S_2 = S_3 = 0$$

The points just evaluated are sufficient to determine the 3 circles and their respective scale lines. The construction of the locus of cross current is shown in Fig. 5. With the circles drawn as indicated in the plot, additional points corresponding to any desired frequencies are determined on the several circles by use of the scale lines. In the figure, such points are shown for 0, 1,000, 2,000, 3,000, 6,000, 8,000, and 16,000 cycles on all 3 circles. The vectors S_1, S_2, and S_3 for each of these frequencies are added together forming the resultant locus of I'_g as indicated. This addition of vectors is shown in the diagram for 1,000 and 6,000 cycles. It should be noticed that the addition of the 3 vectors for 1,000

cycles gives a resultant cross current of zero which is as it should be, since the constants of the network were so chosen as to give null cross current at this frequency.

The locus of I'_o is shown in the figure drawn through the small open circles which represent the terminal points of the summations of S_1, S_2, and S_3 for the various frequencies. For the sake of clarity, the origin in Fig. 5 has been labeled only as I'_o for 1,000 cycles. However, this is also the point corresponding to infinite frequency for all 3 circles and for the locus of I'_o itself, since the cross impedance is infinite at this frequency.

Summary

In a 5-arm network with constant coefficients, consisting of 4 impedance elements arranged in the usual bridge array, with the fifth arm connected across the mid-points, the locus of the cross current flowing through this fifth impedance arm with constant applied voltage at constant frequency is a circle when any one of the network arms is varied at constant phase angle or along one of its components. The circular locus may be determined readily from the network constants and gives the values of cross current as the variable ranges from minus to plus infinity.

When the same network is operated with all its arms fixed at constant applied voltage and the frequency is varied, the locus of the cross current consists of the sum of one or more circles, depending upon the number of network arms which vary with the frequency. In this case the equation for cross current is expressed as the sum of several linear fractional transformations, each of which has a circle for its locus and the resultant locus is obtained by adding corresponding vectors of each circle.

Thus by following the methods described in this paper, the variation of cross current, as any one of the network arms or the frequency of the applied voltage varies, may be readily determined with a minimum of computation. Although the equations for the typical network, used as an illustration, appear somewhat lengthy, it is necessary to evaluate each term of these equations for only one point. This point may be chosen as any positive or negative value of the variable scalar desired, whichever is the most convenient to use under the particular conditions encountered in the network. The other 2 points required to determine the circle are taken at zero and infinity, respectively; both of these values eliminate a considerable number of terms from the equations. The 3 points are sufficient to draw not only the circle but the scale line as well. The result is a diagram from which may be read the magnitude and phase of the cross current for any value of the variable.

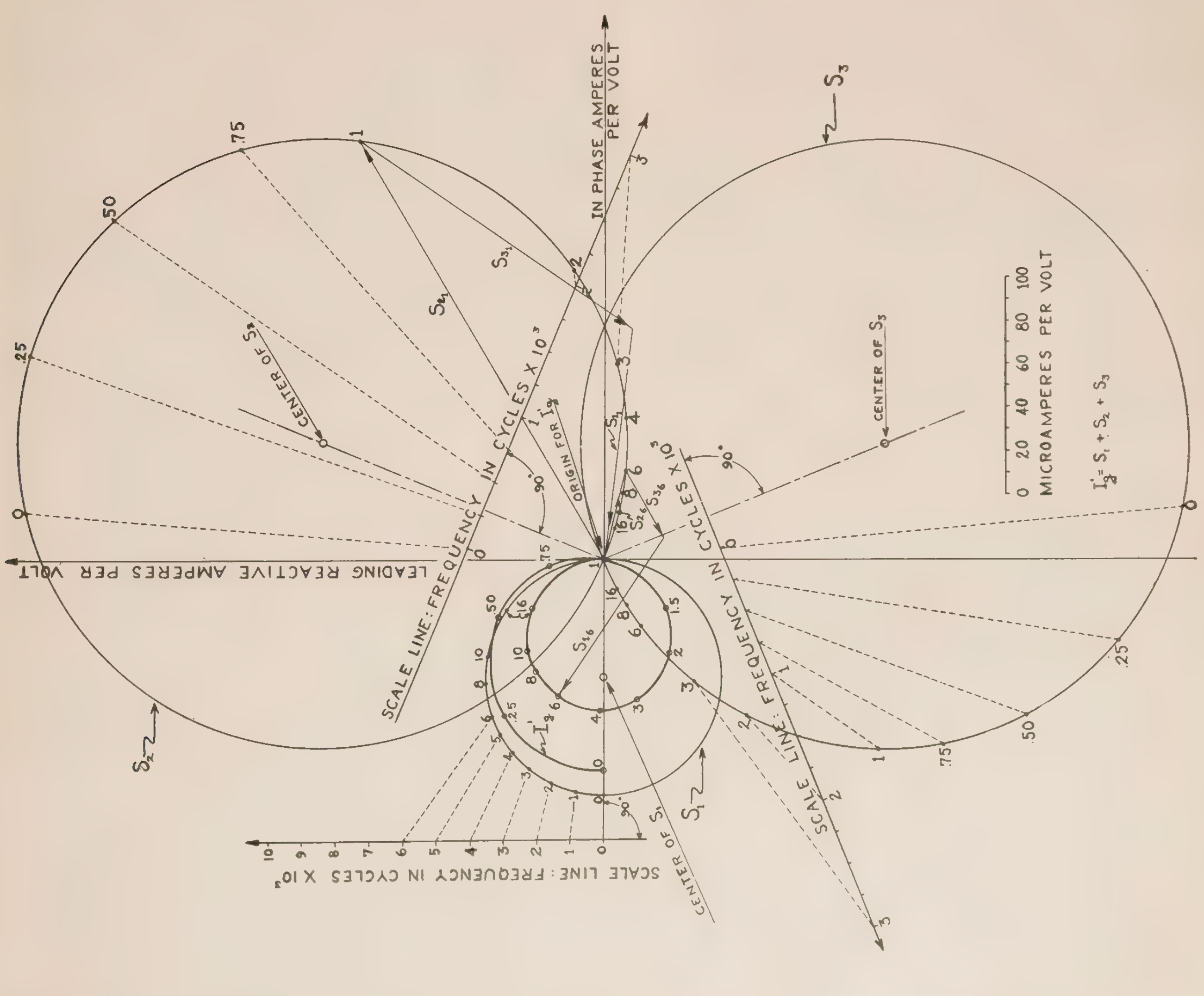

Fig. 5. Construction of the locus of cross current

Insulation Resistance of Armature Windings

Insulation resistance of the windings of an electric machine may be used as a barometer for indicating the condition of the windings. On the basis of tests on many machines of different types it is recommended that all insulation resistance readings be taken after the application of 500 volts (d-c) for one minute. The slope of the resistance-time curve at that point gives a combined indication of the moisture content and the quality of the insulation. In this paper are given formulas for the insulation resistance of different types of windings derived from the winding insulation dimensions and expressed in terms of the rated voltage, capacity, and speed of the machine. By the use of nomographs, insulation resistances can be determined in about 15 second's time; 5 of these prepared for different types of machines are included in the paper.

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INSULATION resistance of an armature winding varies from time to time under operating conditions because the temperature and the humidity of the surrounding air are never constant. Dust and other foreign matter are deposited continuously on the end windings and connections, and the effect of these depends on how often the winding is thoroughly cleaned. Moisture will lower the insulation resistance temporarily, whereas acid or alkali fumes will lower it permanently. Armature winding insulation resistance, therefore, varies over a rather wide range, and experience in obtaining insulation resistances of windings indicates that:

1. A single value of insulation resistance taken at random without knowing the kind of insulation, its construction, and a "bench mark" value for comparison has little significance.

2. Insulation resistance varies inversely with the amount of moisture in the insulation and the amount of solvent left in the bonding varnish of the coil. From this standpoint the insulation resistance should increase gradually with age if the machine is operated in a clean dry place.

3. Insulation resistance varies inversely with temperature. If the winding is clean and dry, its insulation resistance at room temperature (21 deg C) may be 10 or more times the insulation resistance at 75 deg C. Class *A* insulation varies much more with temperature than does class *B* insulation.

4. Insulation resistance varies somewhat with the applied voltage; usually it decreases as the applied voltage increases.

5. Insulation resistance varies with the time of voltage application; usually it increases during the first 10 minutes of voltage application. This variation (dielectric absorption) makes the measurement of a very high insulation resistance somewhat difficult.

6. Duplicate machines built at the same time and under the same manufacturing conditions may have different insulation resistances. Duplicate machines built at different times, but in the same factory, may have *widely* different insulation resistances.

7. A high value of insulation resistance does not necessarily give assurance that the insulation is in good condition and free from cracks, etc., which eventually may result in a failure. A winding that has failed on the end portion, although clean and dry may have a relatively high insulation resistance.

8. A machine that has a relatively low insulation resistance may have sufficient dielectric strength to operate satisfactorily for a long time.

9. The current that flows through the insulation and the leakage current that flows along the surface of the end winding and connections determine the insulation resistance. A low value of resistance, therefore, does not indicate whether the insulation itself has deteriorated or whether the surface leakage is excessive.

10. Machines having the same rating, but different types of insulation, have different insulation resistances. For example, varnished fabric insulation will absorb more moisture than vacuum-dried compound-filled mica insulation. Thus the insulation resistance of a mica winding will give more of an indication of the end surface leakage, whereas that of a varnished fabric insulated winding will give a combined indication of both the end surface leakage and the insulation resistance from copper to ground. Furthermore, if the insulation has a joint at each of the 4 corners of a coil, the end leakage may lower the insulation resistance if the joints are not made properly.

11. A low insulation resistance is the result of several months of moisture accumulation because a winding requires considerable time to absorb moisture. A machine that operates continuously will have a higher insulation resistance than a machine that operates intermittently and allows the insulation to "breathe."

12. Measurement of insulation resistance of a winding whose end winding and connections are encased with dirt will give a false impression of the insulation. In this case the insulation may be in good condition, but excessive end leakage will condemn the winding.

Notwithstanding all these somewhat complicated variations, insulation resistance will indicate to a certain extent when a winding is in satisfactory condition for service or for a reasonably high potential test. This is true if the insulation resistance of a winding can be compared with its resistance when it is known to be in good condition.

For many years the A.I.E.E. STANDARDS specified a minimum insulation resistance at 75 deg C of

$$R_i = \frac{\text{rated voltage}}{\text{rated kva} + 1{,}000}$$

This rule recently was revised to read

$$R_i = \frac{\text{rated voltage}}{\dfrac{\text{rated kva}}{100} + 1{,}000}$$

Neither of these expressions can give a true interpretation of the problem. For example, a d-c motor,

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an induction motor, and an a-c generator, all of the same voltage and capacity, have the same minimum insulation resistance with these formulas. This is not logical because these 3 machines have different constructions, different insulations, and different ratios of insulation thickness to insulation area (t/A). Furthermore, a low speed machine of a given capacity and voltage has inherently a lower insulation resistance than a high speed machine of the same capacity and voltage.

The object of this paper is to describe insulation resistance characteristics of armature windings and to devise formulas for armature winding insulation resistance that take into account:

1. The speed of the machine as well as its capacity and voltage.
2. The different types of machines, such as synchronous, induction, and d-c machines.
3. The kind of coil insulation (class A or class B).
4. Coefficients that will give an "average" value of the insulation resistance when a machine is new; when a machine has had favorable operating conditions (clean and dry); and the minimum insulation resistance which indicates when a winding should be carefully inspected and reconditioned if necessary.

Measurement of Insulation Resistance

Insulation resistance of an armature winding may be measured with an instrument such as a megger, "megohmer," etc.; or with a voltmeter or a microammeter connected in series with the winding and a direct voltage. The megger has been used for many years, and it gives reliable readings if it is calibrated periodically and if it is operated long enough to eliminate the electrostatic capacity effect of the winding. With the voltmeter method, the maximum resistance that can be measured with reasonable accuracy is about 10 megohms when an ordinary voltmeter is used and about 100 megohms when a high resistance voltmeter is used. From the operator's viewpoint, however, a resistance above 100 megohms for any machine is considered satisfactory. The microammeter method is very accurate for measuring high insulation resistances if a storage battery furnishes the voltage.

Variation of Insulation Resistance

When a constant voltage from a d-c source is impressed on insulation, the current is a maximum at the instant of voltage application; it then decreases at a variable rate in accordance with the type and condition of the insulation. The current is composed of 3 distinct components with different time-constants somewhat as the short-circuit current of an a-c generator is composed of the subtransient, transient, and synchronous reactance components. The corresponding insulation current components are due to electrostatic capacity, dielectric absorption, and conduction-leakage.

Immediately on the application of a constant voltage from a d-c source a normal charging current will flow corresponding to the capacitance of the winding (and to the resistance and inductance of the circuit). This normal charging current, however, usually disappears in less than a second and it should be neglected by short-circuiting the meter for a few seconds after the voltage is applied. After the normal charging current has disappeared, the insulation continues to draw a polarization charging current at a decreasing rate. This polarization current is caused by dielectric absorption; and if the insulation is relatively dry, the polarization current may decrease slowly for several hours (in the case of cables for several days). The polarization current is not proportional to the applied voltage, but varies somewhat as the magnetizing current of iron. After the dielectric absorption current dies away, the conduction and leakage currents of the winding continue.

The true resistance is obtained by dividing the applied voltage by the current when it has reached its constant minimum value. The true resistance can be obtained also by dividing the applied voltage by the difference between the charging current at a given time and the discharge current at the same time interval. Both of these methods of measuring the true insulation resistance are somewhat cumbersome in the field; consequently, it is more practical to measure an "apparent" insulation resistance which includes some absorption. It is obvious, therefore, that in measuring the apparent insulation resistance,

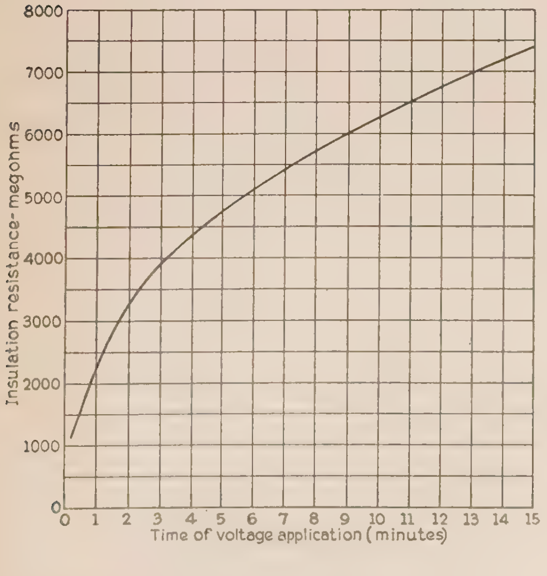


Fig. 1 (left). Armature winding insulation resistance of a new 750-kva 327-rpm 2,400-volt class A insulated a-c generator

Applied voltage 500 volts (d-c); winding temperature 17 deg C. Insulation resistance measured on a dry winter day

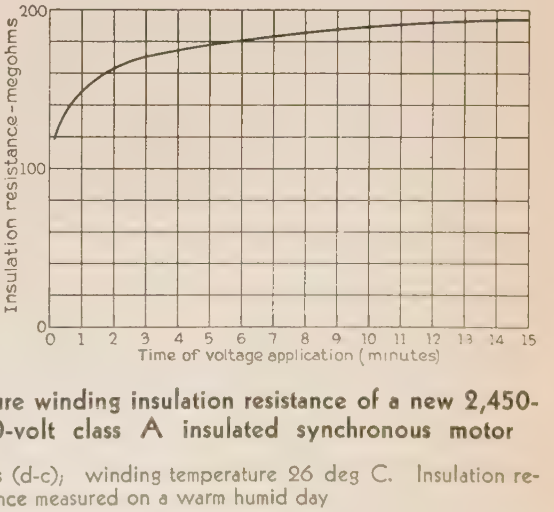


Fig. 2 (right). Armature winding insulation resistance of a new 2,450-kva 750-rpm 6,600-volt class A insulated synchronous motor

Applied voltage 500 volts (d-c); winding temperature 26 deg C. Insulation resistance measured on a warm humid day

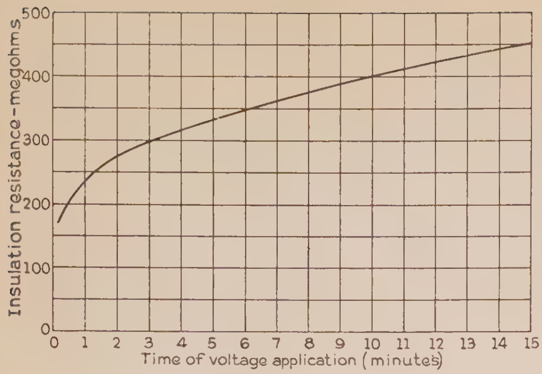
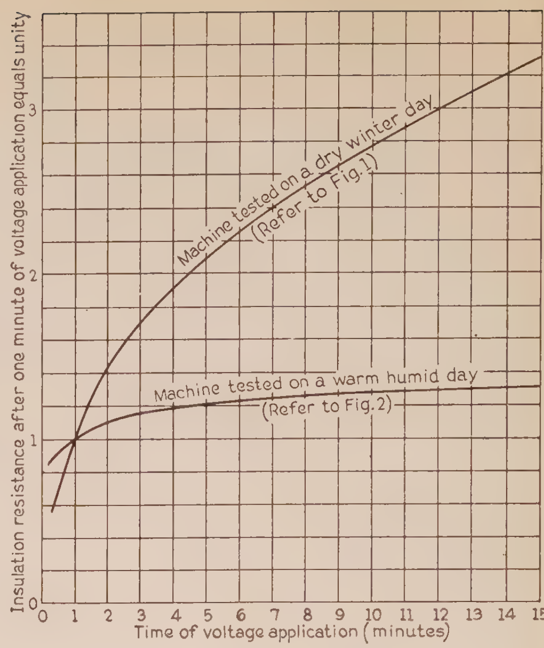


Fig. 3 (left). Armature winding insulation resistance of a new 1,250-kw 750-rpm 600-volt d-c generator

Applied voltage 500 volts (d-c); winding temperature 22 deg C

Fig. 4 (right). Per-unit insulation resistance



the applied voltage and the time of voltage application should be taken into consideration.

Dielectric absorption, notwithstanding its variable characteristics, can be used to advantage in determining the condition of armature insulation. If the conduction current is large, it will over-shadow the polarization current so that the polarization effect cannot be observed. In this case the current will reach its minimum value very quickly. If the insulation is dry, its conduction current will be small and the polarization effect can readily be observed. If the insulation resistance-time curve of a winding, therefore, increases appreciably after 2 or 3 minutes of voltage application, the insulation has a low moisture content. If the resistance-time curve does not increase to any extent after 2 or 3 minutes of voltage application, the insulation either has a high moisture content or the end leakage is excessive.

The insulation resistance of a large number of new machines was measured by the microammeter method for a 15-min voltage application from a 500-volt storage battery. The current was not recorded until 10 seconds had elapsed after the voltage was applied in order to eliminate the capacitance effect of the winding. The insulation resistance of the machines also was checked with a megger.

Figure 1 shows an insulation resistance-time curve of a synchronous machine that was built and tested in the winter when the insulation was dry and cold. Figure 2 shows the insulation resistance of a synchronous machine that was built in the summer and tested on a warm humid day. Figure 3 shows the insulation resistance of a d-c generator tested in the summer when the relative humidity of the air was about 60 per cent.

The curves in Figs. 1 and 2 are replotted in Fig. 4 on the basis that the insulation resistance after one minute of voltage application is unity. The lower curve indicates that the conduction current through the insulation and the leakage current over the end windings and connections are much larger than the absorption current. Thus the absorption effect in this case plays only a *very small* part in the resistance-time curve. The upper curve indicates that the conduction and leakage currents are small and so the absorption current plays an *important* part in shaping the resistance-time curve.

Figure 5 shows curves of several new a-c and d-c machines similar to the curves in Fig. 4, but plotted on a log-log scale. Curves 1 and 2, Fig. 5, show the insulation resistance characteristics of machines in the summer, curves 3 and 4 in the spring, curves 5, 6, and 7 in the fall, and curves 8, 9, and 10 in the winter. In other words, the slope of the curve increases as the moisture content of the insulation decreases. From 0.2 to 0.8 min of voltage application, insulation resistance-time characteristics, Fig. 5, are curved slightly. At 1 minute of voltage application the curve is a straight line (that is, a simple power function of time) and the slope of the curve has a constant value. After 2 or 3 minutes it may curve again slightly or it may continue as a straight line up to 10 minutes. A voltage application of 1 min, therefore, was chosen as the time of voltage application for measuring insulation resistances of armature windings.

How the insulation resistance varies with the time of voltage application, with the applied voltage, and with the winding temperature, is shown in Fig. 6. In Fig. 7 the upper curve shows a polarization charging current curve of a new 10,000-kva 214-rpm 6,900-volt Class-B-insulated a-c generator when 500 volts was applied to the armature winding. The lower curve shows the discharge current when the winding was grounded after it was fully charged. The difference between these 2 curves is the true resistance current curve (dotted line). Theoretically the true resistance current curve is the asymptote of the charging current curve. The variation of apparent insulation resistance of this machine with time of voltage application is as follows:

Time of Voltage Application, Minutes	Insulation Resistance, Megohms
0.25	310
0.5	500
1	820
2	1,350
3	1,730
5	2,400
10	3,600
∞	6,000

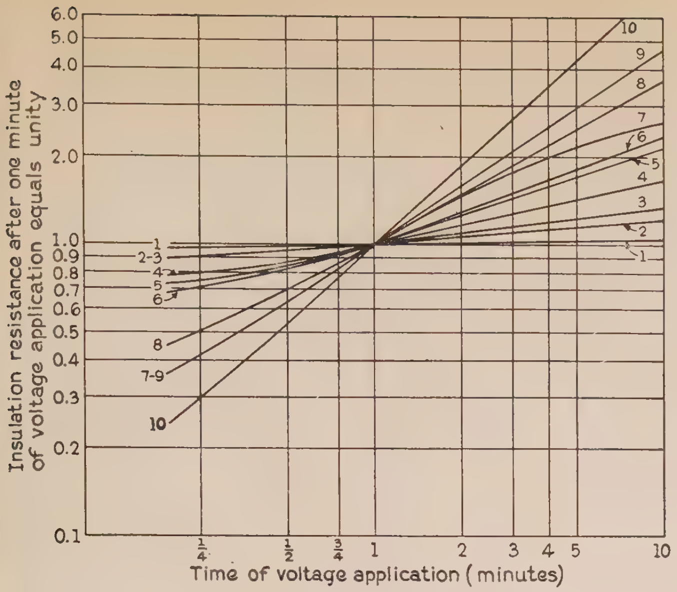


Fig. 5. Per-unit insulation resistance

1. 625-kva 150-rpm 2,300-volt a-c generator
2. 300-kva 225-rpm 2,200-volt synchronous motor
3. 312-kva 360-rpm 240-volt a-c generator
4. 1,250-kw 750-rpm 600-volt d-c generator
5. 400-kw 750-rpm 300-volt d-c generator
6. 750-kw 750-rpm 600-volt d-c generator
7. 2,100-kva 514-rpm 11,000-volt synchronous motor
8. 850-kva 750-rpm 10,500-volt synchronous motor
9. 800-hp 400-rpm 600-volt d-c motor
10. 10,000-kva 214-rpm 6,900-volt a-c generator

The importance of specifying the conditions under which armature winding insulation resistance is measured is shown by Figs. 6 and 7. In order to obtain consistent results, therefore, it is proposed to measure the apparent insulation resistance of armature windings with 500 volts after a voltage application of 1-min duration.

Formulas for Armature Winding Insulation Resistance

To obtain a formula for the insulation resistance of an armature winding in a simplified form (see Appendix) it is necessary to make reasonable assumptions and to use "average values" for factors such as electric and magnetic loading, number of slots, size of slot, thickness of insulation, and diameter and length of a machine, which vary somewhat from one machine to another. The following formulas, therefore, apply to maximum continuous rated (50 deg C rise by thermometer or 60 deg C rise by imbedded temperature detector) a-c and d-c machines and to induction motors of normal design and standard construction that are rated for a 40 deg C rise. In determining the insulation resistance of a special machine or of an old machine, the capacity rating as just outlined and the corresponding speed and voltage should be used. A single-phase machine should have its capacity rating increased about 50 per cent if the machine is wound with a 3-phase Y-connected winding. A suitable allowance also should be made for special features of a machine.

It is somewhat cumbersome, and in fact unnecessary, to take into account all the insulation features of small machines of less than 100 kva or hp. Furthermore, these machines can be and are used with relatively lower insulation resistances than large machines. It is suggested, therefore, that for machines of less than 100 kva or hp, 100 be used when substituting in the formulas regardless of the actual rating of the machine.

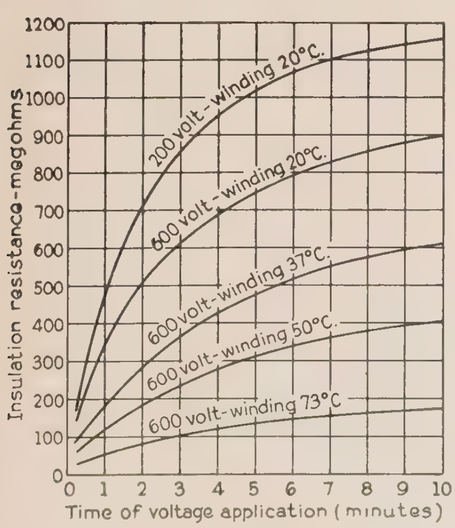


Fig. 6. Variation of insulation resistance of a new 2,100-kva 514-rpm 11,000-volt synchronous motor with applied voltage and temperature

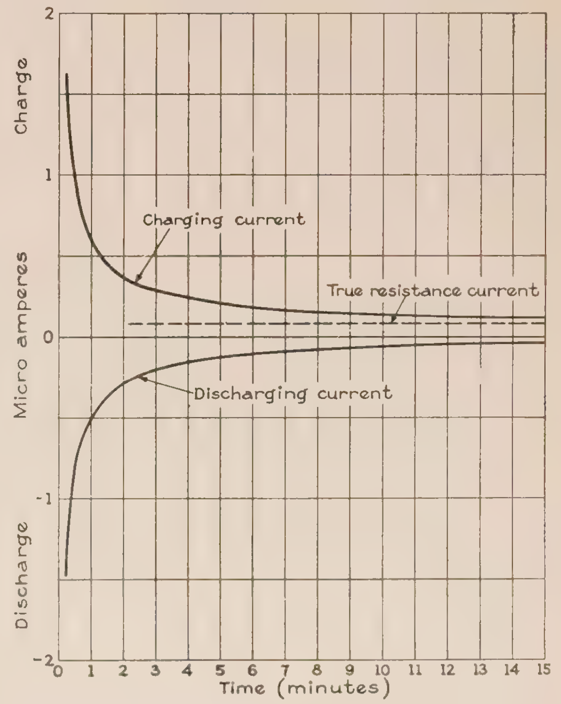


Fig. 7. Insulation charging and discharging current curves of a new 10,000-kva 214-rpm 6,900-volt class B insulated armature winding

Applied voltage 500 volts (d-c); winding temperature 17 deg C

Synchronous Motors and Generators. The insulation resistance R_i of a stator winding of a synchronous machine (a-c generator, synchronous motor, synchronous condenser, and synchronous rotary phase converter) expressed as a function of the machine rated voltage, speed in revolutions per minute (rpm), and kilovoltamperes (kva), as meas-

Table I—Insulation Resistance Coefficients

Condition of Machine	Winding Temperature, Degrees C	Synchronous Machines: Above 1,000 Kva k_s, Class A Insulated	Synchronous Machines: Above 1,000 Kva k_s, Class B Insulated	Synchronous Machines: Below 1,000 Kva k_{ss}, Class A Insulated	Synchronous Machines: Below 1,000 Kva k_{ss}, Class B Insulated	Induction Motors k_i, Class A Insulated	Induction Motors k_i, Class B Insulated	D-C Machines k_d	Synchronous Converters k_c
1. New, clean, and dry (built in the winter; relative humidity 10%)	21	2.0	3.0	0.35	0.50	0.1	0.14	0.1	0.1
2. New and clean (built in the summer; relative humidity 90%)	21	0.4	1.0	0.07	0.15	0.02	0.04	0.02	0.02
3. Good operating conditions (clean and dry)	21	0.5	1.4	0.07	0.2	0.015	0.04	0.01	0.008
4. The winding should be carefully inspected, reconditioned, cleaned, dried, and the end winding varnished if the resistance is less than the values given by these coefficients	75	0.005	0.1	0.0008	0.015	0.0002	0.004	0.0001	0.00007

Table II—Comparison of Present and Proposed Minimum Insulation Resistances (Megohms) of Synchronous Machine Armature Windings at 75 Deg C

Machine Rating: Kva	Machine Rating: Speed Rpm	Machine Rating: Voltage	Present A.I.E.E. Standards $\frac{E}{\text{Kva}+1{,}000}$	Proposed A.S.A. Standards $\frac{E}{\frac{\text{Kva}}{100}+1{,}000}$	Proposed Formula: $k_s=0.005$ or $k_{ss}=0.0008$, Class A Insulated	Proposed Formula: $k_s=0.1$, Class B Insulated
100	100	200	0.18	0.20	1.4	
100	100	4,000	3.64	4.00	2.8	
100	600	200	0.18	0.20	2.6	
100	600	4,000	3.64	4.00	5.1	
100	1,800	200	0.18	0.20	3.7	
100	1,800	4,000	3.64	4.00	7.4	
1,000	100	500	0.25	0.49	0.53	
1,000	100	10,000	5.00	9.90	1.8	35
1,000	600	500	0.25	0.49	0.97	
1,000	600	10,000	5.00	9.90	3.2	64
1,000	1,800	500	0.25	0.49	1.4	
1,000	1,800	10,000	5.00	9.90	4.6	93
10,000	100	2,000	0.18	1.8	0.13	2.6
10,000	100	15,000	1.36	13.6		8.6
10,000	600	2,000	0.18	1.8	0.24	4.7
10,000	600	15,000	1.36	13.6		15.7
10,000	1,800	2,000	0.18	1.8	0.34	6.8
10,000	1,800	15,000	1.36	13.6		22.6
50,000	100	5,000	0.10	3.3		1.2
50,000	100	15,000	0.29	10.0		2.6
50,000	600	5,000	0.10	3.3		2.2
50,000	600	15,000	0.29	10.0		4.7
50,000	1,800	5,000	0.10	3.3		3.1
50,000	1,800	15,000	0.29	10.0		6.7
100,000	100	10,000	0.10	5.0		1.1
100,000	100	20,000	0.20	10.0		2.0
100,000	600	10,000	0.10	5.0		2.1
100,000	600	20,000	0.20	10.0		3.5
100,000	1,800	10,000	0.10	5.0		3.0
100,000	1,800	20,000	0.20	10.0		5.1

ured after a 1-min application of 500 volts is approximately

$$R_i = k_s \frac{(\text{voltage} + 3{,}600)\ \text{rpm}^{1/3}}{\text{kva}^{3/4}} \quad \text{for machines of more than 1,000 kva} \tag{1}$$

$$R_i = k_{ss} \frac{(\text{voltage} + 3{,}600)\ \text{rpm}^{1/3}}{\text{kva}^{1/2}} \quad \text{for machines of less than 1,000 kva} \tag{2}$$

Induction Motors. The insulation resistance R_i of a stator winding of an induction motor expressed as a function of the machine rated voltage, speed in revolutions per minute (rpm), and horsepower, as measured after a 1-min application of 500 volts is approximately

$$R_i = k_i \frac{(\text{voltage} + 3{,}600)\ \text{rpm}^{1/2}}{\text{hp}^{1/2}} \tag{3}$$

Direct-Current Motors and Generators. The insulation resistance R_i of a rotor armature winding of a d-c motor or generator expressed as a function of the machine rated voltage, speed in revolutions per minute, and kilowatts (kw), as measured after a 1-min application of 500 volts is approximately

$$R_i = k_d \frac{(\text{voltage} + 1{,}400)\ \text{rpm}^{1/2}}{\text{kw}^{1/3}} \tag{4}$$

Synchronous Converters. The insulation resistance R_i of a rotor armature winding of a synchronous converter expressed as a function of the machine rated voltage, speed in revolutions per minute (rpm), and kilowatts (kw), as measured after a 1-min application of 500 volts is approximately

$$R_i = k_c \frac{(\text{voltage} + 1{,}000)\ \text{rpm}^{1/2}}{\text{kw}^{1/4}} \tag{5}$$

For d-c machines R_i is the insulation resistance of only the armature winding and commutator. No attempt was made to include the insulation resistance of the brushholders, brushholder supports, and field windings because they vary greatly in type and

Table III—Comparison of Present and Proposed Minimum Insulation Resistances (Megohms) of D-C Machine Armature Windings at 75 Deg C

Machine Rating: Kw	Machine Rating: Speed Rpm	Machine Rating: Voltage	Present A.I.E.E. Standards $\frac{E}{\text{Kw}+1{,}000}$	Proposed A.S.A. Standards $\frac{E}{\frac{\text{kw}}{100}+1{,}000}$	Proposed Formula $kd=0.0001$
100	100	100	0.09	0.10	0.32
100	100	600	0.55	0.60	0.43
100	2,000	100	0.09	0.10	1.44
100	2,000	600	0.55	0.60	1.92
500	100	200	0.13	0.20	0.20
500	100	600	0.40	0.60	0.25
500	1,000	200	0.13	0.20	0.64
500	1,000	600	0.40	0.60	0.80
1,000	100	200	0.10	0.20	0.16
1,000	100	600	0.30	0.60	0.20
1,000	720	200	0.10	0.20	0.43
1,000	720	600	0.30	0.60	0.54
2,500	100	200	0.057	0.20	0.12
2,500	100	600	0.17	0.59	0.15
2,500	500	200	0.057	0.20	0.26
2,500	500	600	0.17	0.59	0.33
5,000	100	600	0.10	0.57	0.12
5,000	300	600	0.10	0.57	0.20
10,000	100	600	0.055	0.55	0.09

Table IV—Comparison of Present and Proposed Minimum Insulation Resistances (Megohms) of Synchronous Converter Armature Windings at 75 Deg C

Machine Rating			Present A.I.E.E. Standards	Proposed A.S.A. Standards	Proposed Formula
Kw	Speed Rpm	Voltage	$\frac{E}{kw+1,000}$	$\frac{E}{\frac{kw}{100}+1,000}$	$k_c=0.00007$
100	1,200	100	0.09	0.10	0.84
100	1,200	300	0.27	0.30	1.00
300	1,200	200	0.15	0.20	0.70
300	1,200	600	0.46	0.60	0.93
500	750	200	0.13	0.20	0.50
500	750	600	0.40	0.60	0.67
500	1,200	200	0.13	0.20	0.61
500	1,200	600	0.40	0.60	0.82
1,000	500	200	0.10	0.20	0.33
1,000	750	600	0.30	0.59	0.55
1,000	900	200	0.10	0.20	0.45
1,000	900	600	0.30	0.59	0.60
2,000	300	200	0.07	0.20	0.22
2,000	375	600	0.20	0.59	0.33
2,000	450	200	0.07	0.20	0.36
2,000	600	600	0.20	0.59	0.41
3,000	400	600	0.15	0.58	0.34
5,000	240	600	0.10	0.57	0.21

construction. Thus in measuring the insulation resistance of a d-c machine or a synchronous converter, all brushes should be raised from the commutator and collector.

Insulation Resistance Coefficients k_s, k_{ss}, k_i, k_d, and k_c. Table I gives values of the insulation coefficients for eqs 1 to 5 for different types of machines. The average range of insulation resistance variation of new machines at room temperature (21 deg C) is given by conditions 1 and 2. If a machine is built in the winter and its insulation resistance measured when the temperature is below 21 deg C, the value of k will be much more than that given for condition 1. Condition 3 gives the values of k for good operating conditions. Machines operating in some localities, however, may not have insulation resistances as high as those corresponding to condition 3.

Condition 4 gives values of k for the minimum insulation resistance of a winding at 75 deg C. Values of k for conditions 3 and 4 were purposely made a little high in order to encourage operators to clean the machines frequently. It is emphasized that a winding having a lower resistance than the minimum value will not necessarily fail. In fact under ordinary operating conditions the resistance occasionally may fall a little below the minimum value. It is believed, however, that if the resistance is maintained at or above that corresponding to k for condition 4, the winding should give reliable service.

In deriving eqs 1, 2, 3, 4, and 5, all constants were incorporated in the coefficient k for simplicity. The fact that different machines have different values of k for the same class of insulation, Table I, does not prove that the insulation resistivity of these machines is necessarily different or that the insulation on one type of machine is superior to that of another.

Tables II, III, IV, and V show how the minimum value of insulation resistance obtained by the equations developed compare with those of the present A.I.E.E. STANDARDS and those proposed by the American Standards Association. In some cases the difference is not appreciable, but in others a marked difference results when the type of machine, its speed, and its class of insulation are taken into consideration.

Variation of Insulation Resistance With Temperature and High Humidity

Values of k for condition 4 were determined by test for different kinds of insulation exposed to a high relative humidity. The variation of resistivity

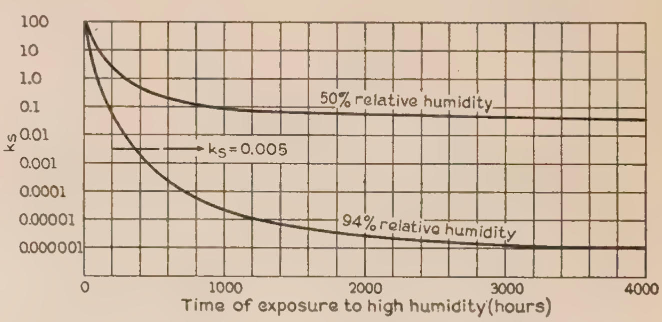


Fig. 8. Variation of resistivity coefficient k_s of class A insulation with time of exposure to high relative humidity at 30 deg C

of Class *A* insulation as measured after a 1-min application of 500 volts with time of exposure to high humidity is shown in Fig. 8. For convenience the resistivity was plotted in terms of k_s for synchronous machines of more than 1,000 kva so that a comparison can be made with the values of k_s in Table I. The insulation was "bone-dry" when the test was

Table V—Comparison of Present and Proposed Minimum Insulation Resistances (Megohms) at 75 Deg C

Machine Rating							All Machines	
Kva	Speed Rpm	Voltage	Synchronous Machines	Induction Motors	D-C Machines	Synchronous Converters	A.I.E.E. Standards	A.S.A. Standards
100	1,000	200	3.0	2.4	1.1	0.84	0.18	0.5
500	1,000	200	1.4	1.1	0.64	0.56	0.13	0.2
500	1,000	600	1.5	1.2	0.80	0.75	0.3	0.5
1,000	300	200	0.72	0.42	0.28	0.26	0.1	0.2
1,000	300	1,000	0.87	0.51	0.42	0.43	0.5	1.0
1,000	1,000	200	1.07	0.76	0.51	0.47	0.1	0.2
1,000	1,000	1,000	1.29	0.92	0.76	0.79	0.5	1.0
5,000	300	1,000	0.26	0.23	0.24	0.29	0.17	0.95

begun, which accounts for the high initial value of k_s.

The variation of k_s in Fig. 8 with time of exposure to high humidity does not take into account the accumulation of dirt and other foreign matter on the winding. A practical test to include all variables is somewhat difficult to make and so the effect of each of these should be determined separately. Table I, therefore, is a composite evaluation of k for different types of machines as determined by resistivity tests on insulation samples and on old and new machines.

The resistivity of dry varnished fabric insulation (Class A) was found by test to decrease about 75 times as much as the resistivity of mica insulation (Class B) for a temperature increase from 21 deg C to 75 deg C as measured after a one-minute application of 500 volts. Tests also show that the resistivity of varnished fabric insulation decreases 10 or more times as much as the resistivity of mica insulation when exposed to high humidities. Higher values, therefore, were assigned to k, Table I, for mica insulation than for varnished fabric insulation. Furthermore, mica insulated machines are usually large, important machines and they should be maintained at a relatively higher insulation resistance than varnished fabric insulated machines.

Summarization

Insulation resistance will serve as a useful barometer for indicating the condition of a winding. In the case of a new machine just installed, the insulation resistance will indicate when the drying-out process may be discontinued. In the case of a machine that has been idle for some time, the insulation resistance will indicate if the machine is in a satisfactory condition for service, provided a careful inspection is made to insure that the end windings and connections are not damaged mechanically. Insulation resistance, however, will not indicate exactly when a winding will fail. Judgment, therefore, must be used in interpreting insulation readings and in deciding when a winding should be reconditioned or reinsulated.

Insulation resistance readings of a machine should be taken after an application of 500 volts for one minute. The winding temperature always should be recorded, and readings should be taken at regular intervals. The trend or slope of the curve of insulation resistance will indicate the condition of the insulation better than insulation resistance values themselves. If an insulation resistance curve of a machine is not available, insulation resistance obtained by the formula for conditions 3 and 4, Table I, can be used as a basis for comparison.

An insulation resistance-time curve plotted on a log-log scale (see Fig. 5) will give a very good indication of the condition of the insulation. If the curve tends to increase after 1 or 2 minutes of voltage application, the moisture content and the end surface leakage are small. The more the curve continues as a straight line after 1 or 2 minutes of voltage application, the better the condition of the winding insulation. Conversely, if the slope of the curve at one-minute voltage application is small, the insulation has absorbed moisture or the end leakage is excessive.

Insulation resistance formulas based on the dimensions of a machine are recommended in the place of formulas that include only the machine voltage and capacity rating, but make no allowance for the type of machine, its speed, and its kind of insulation. Insulation resistance in accordance with the method recommended in this paper can be determined in about 15 seconds from nomographs, Figs. 9 to 13.

Insulation resistance may not indicate if the insulation has localized weak spots or whether the insulation has a high power factor. An insulation resistance test, therefore, does not take the place of either a power factor test or a high potential test. Periodic insulation resistance tests, however, are recommended as a fundamental method of checking the condition of the winding insulation.

Appendix—Insulation Resistance of Synchronous Machines of More Than 1,000 Kva

The insulation resistance in megohms of an armature winding after a 1-min application of 500 volts is

$$R_i = k\frac{t}{A} \tag{6}$$

where

k = a function of the winding moisture content, kind of insulation, operating conditions, and average resistivity of armature insulation after a one-minute application of 500 volts

t = average insulation thickness from copper to ground, in inches

t = 0.052 + 0.0000145 E approximately (7)

E = machine rated voltage

A = effective area of insulation from copper to ground, in square inches

The stator slot pitch in inches is approximately

$$t_0 = 0.9 + 0.000088\,E \tag{8}$$

The stator slot periphery minus the stator slot wedge depth and the stator slot width is approximately

$$p = 4.5 + 0.00044\,E \tag{9}$$

The gap diameter in inches is approximately

$$D = 127\,\frac{\text{kva}^{\frac{0.42}{\text{rpm}^{0.1}}}}{\text{rpm}^{0.39}} \tag{10}$$

The stator core length in inches, increased slightly to allow for end leakage currents, is approximately

$$L = 0.41\,\text{rpm}^{0.05}\cdot\text{kva}^{0.32\,\text{rpm}^{0.06}} \tag{11}$$

$$A = \frac{\pi D}{t_0}\,pL \tag{12}$$

Substituting eqs 8, 9, 10, and 11 in eq 12,

$$A = 815\,\frac{\text{kva}^{\frac{0.74}{\text{rpm}^{0.04}}}}{\text{rpm}^{0.34}} \tag{13}$$

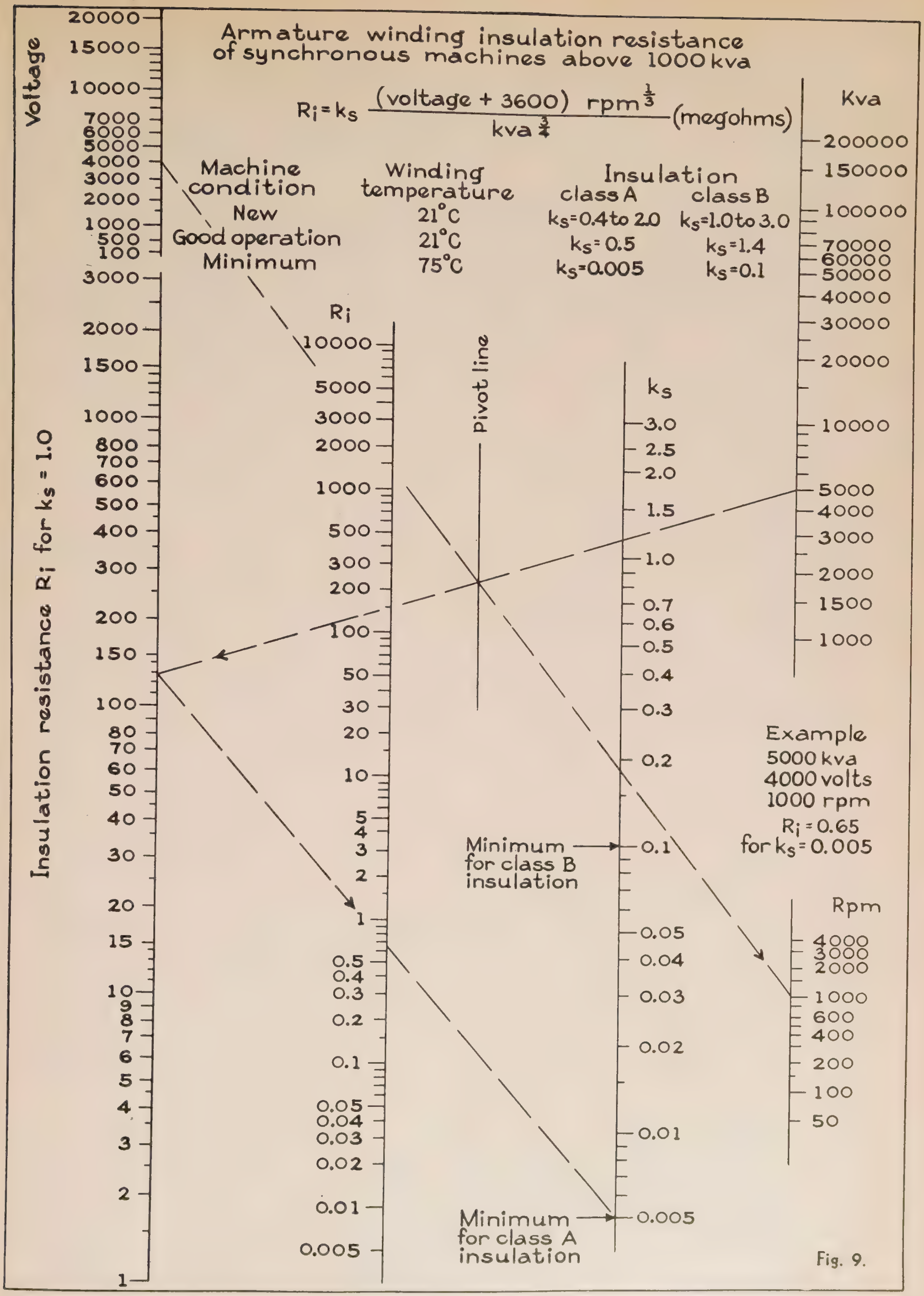
This expression was checked with a large number of machines and it was found that it can be written

$$A = 420\,\frac{\text{kva}^{3/4}}{\text{rpm}^{1/3}}\ \text{approximately} \tag{14}$$

Substituting eqs 7 and 13 in eq 6,

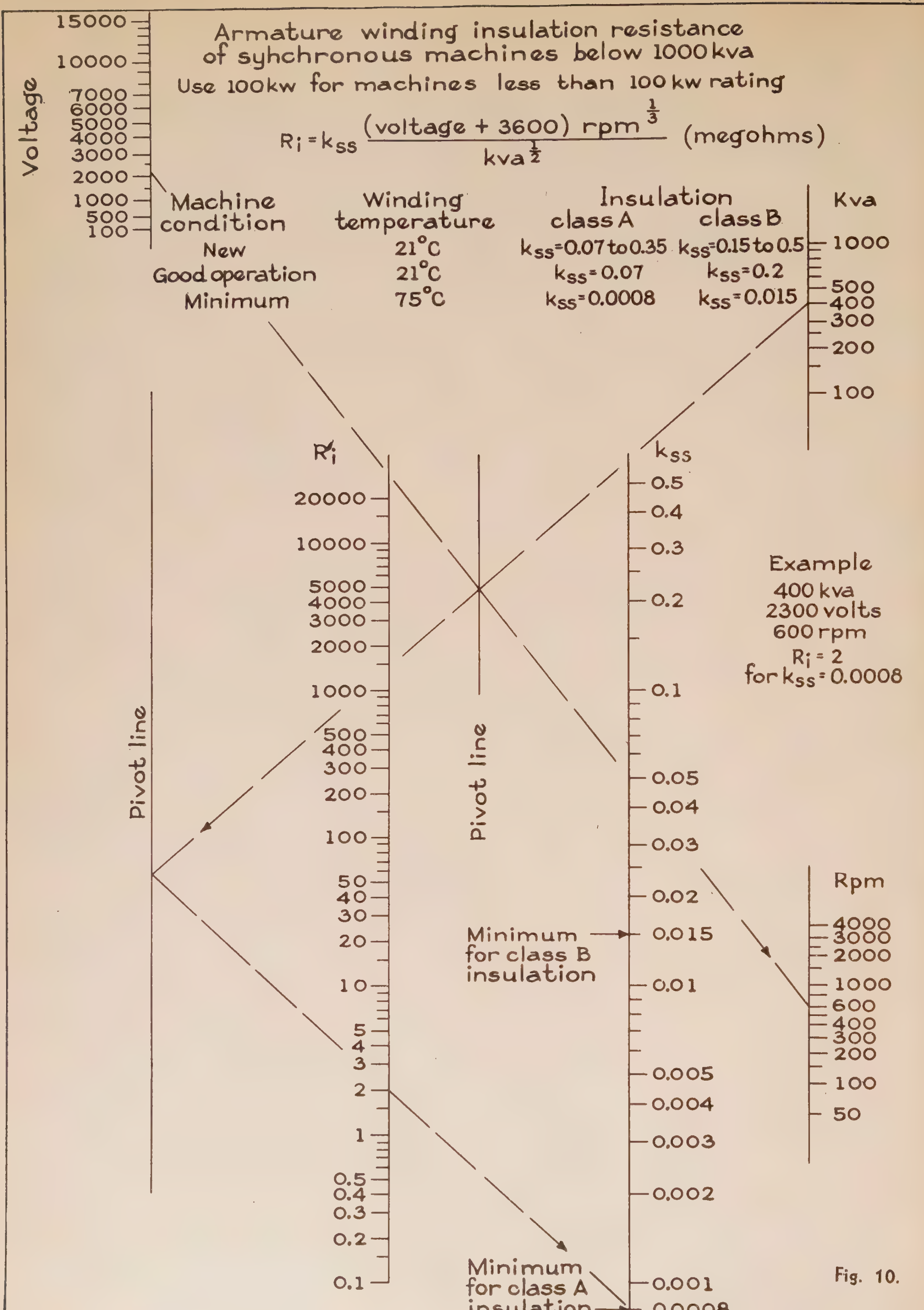
$$R_i = k_s\,\frac{(3{,}600 + E)\text{rpm}^{1/3}}{\text{kva}^{3/4}} \tag{15}$$

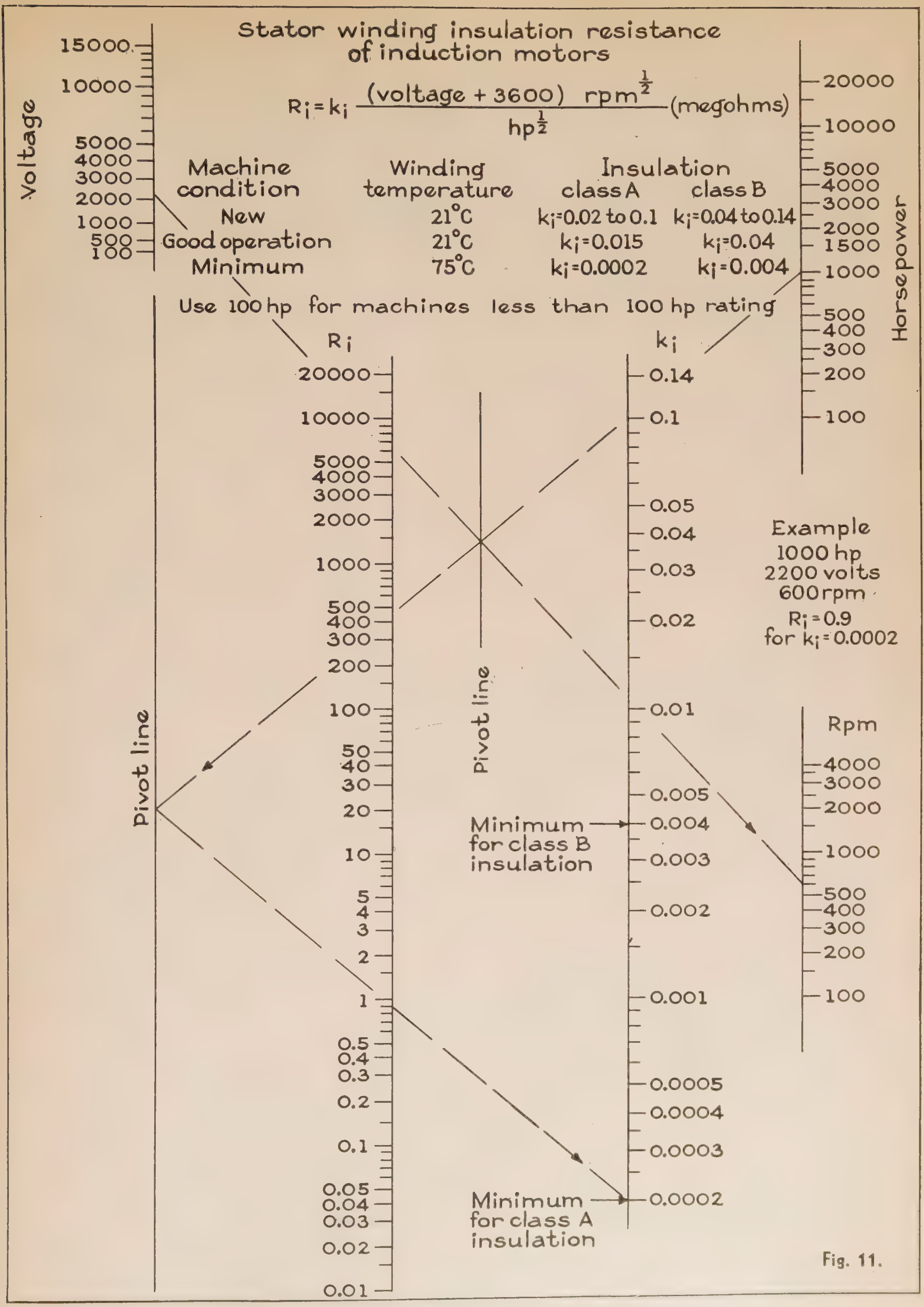
In this manner R_i can be obtained for induction motors, d-c machines, and synchronous converters.

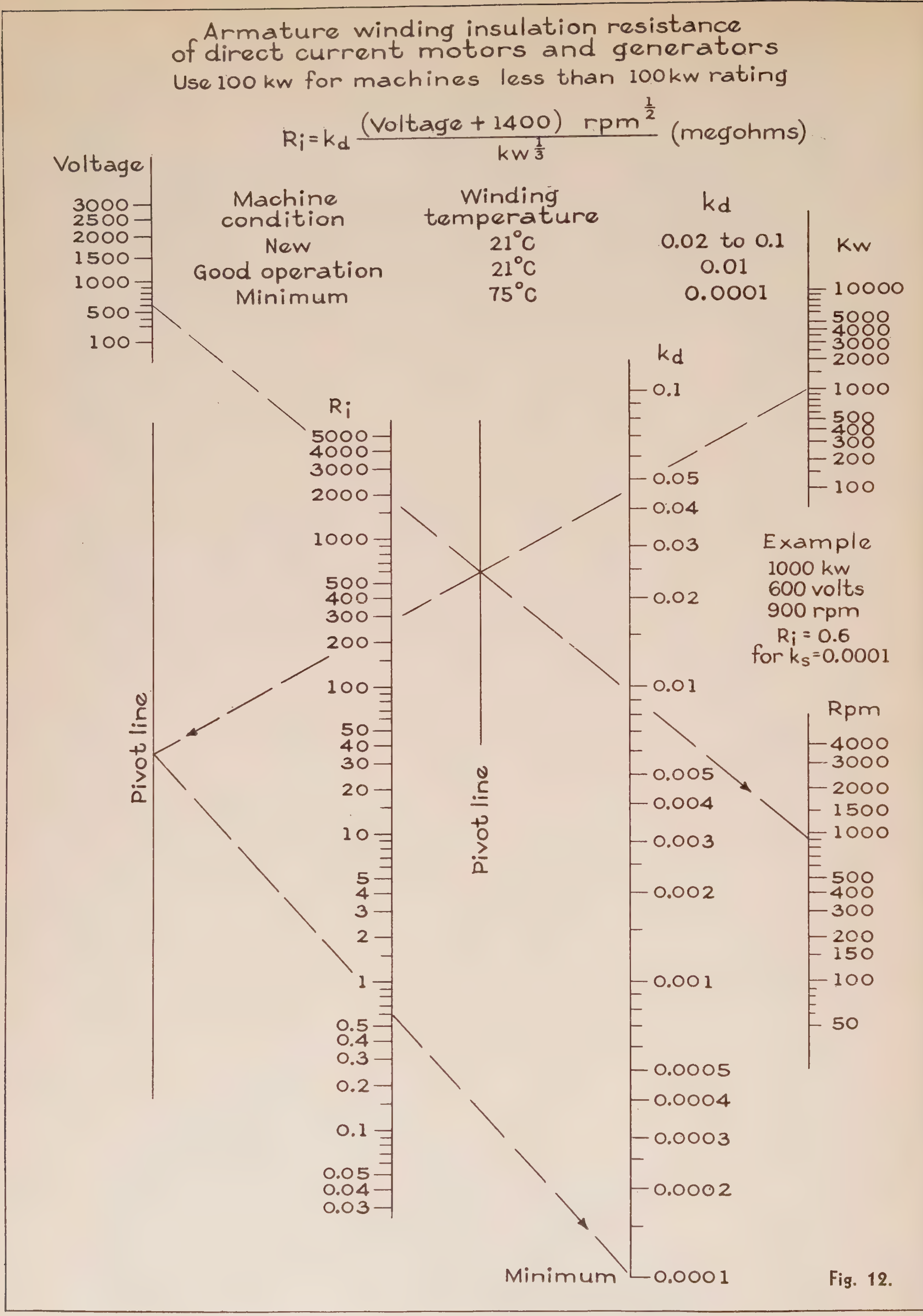


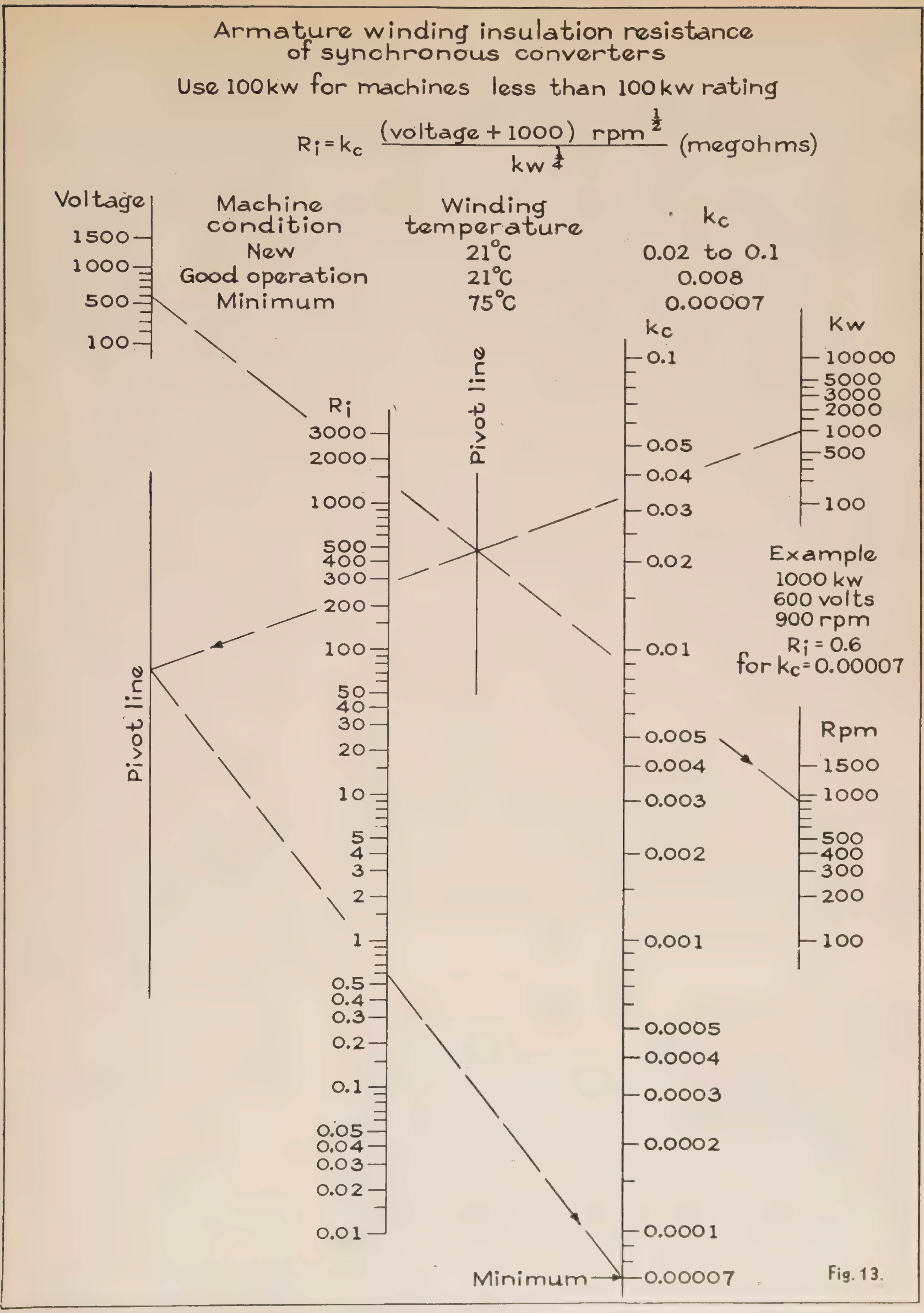
Armature winding insulation resistance of synchronous machines above 1000 kva
$R_i = k_s \frac{(\text{voltage} + 3600)\ \text{rpm}^{\frac{1}{3}}}{\text{kva}^{\frac{3}{4}}}$ (megohms)
Voltage
Insulation resistance R_i for k_s = 1.0
Machine condition
New
Good operation
Minimum
Winding temperature
21°C
21°C
75°C
Insulation
class A
k_s=0.4 to 2.0
k_s= 0.5
k_s=0.005
class B
k_s=1.0 to 3.0
k_s=1.4
k_s=0.1
R_i
Pivot line
k_s
Kva
Rpm
Minimum for class B insulation
Minimum for class A insulation
Example
5000 kva
4000 volts
1000 rpm
R_i = 0.65
for k_s = 0.005

Fig. 9.


Armature winding insulation resistance of syhchronous machines below 1000 kva
Use 100 kw for machines less than 100 kw rating
$R_i = k_{ss} \frac{(\text{voltage} + 3600)\ \text{rpm}^{\frac{1}{3}}}{\text{kva}^{\frac{1}{2}}}$ (megohms)
Voltage
15000
10000
7000
6000
5000
4000
3000
2000
1000
500
100
Machine condition
Winding temperature
Insulation
class A
class B
New
21°C
k_{ss}=0.07 to 0.35
k_{ss}=0.15 to 0.5
Good operation
21°C
k_{ss}=0.07
k_{ss}=0.2
Minimum
75°C
k_{ss}=0.0008
k_{ss}=0.015
Kva
1000
500
400
300
200
100
R_i
20000
10000
5000
4000
3000
2000
1000
500
400
300
200
100
50
40
30
20
10
5
4
3
2
1
0.5
0.4
0.3
0.2
0.1
Pivot line
Pivot line
k_{ss}
0.5
0.4
0.3
0.2
0.1
0.05
0.04
0.03
0.02
0.015
0.01
0.005
0.004
0.003
0.002
0.001
0.0008
Minimum for class B insulation
Minimum for class A insulation
Example
400 kva
2300 volts
600 rpm
R_i = 2
for k_{ss} = 0.0008
Rpm
4000
3000
2000
1000
600
400
300
200
100
50
Fig. 10.


Stator winding insulation resistance of induction motors
Ri = ki (voltage + 3600) rpm½ / hp½ (megohms)
Machine condition
Winding temperature
Insulation
class A
class B
New
21°C
ki=0.02 to 0.1
ki=0.04 to 0.14
Good operation
21°C
ki=0.015
ki=0.04
Minimum
75°C
ki=0.0002
ki=0.004
Use 100 hp for machines less than 100 hp rating
Voltage
Horsepower
Ri
ki
Rpm
Pivot line
Pivot line
Minimum for class B insulation
Minimum for class A insulation
Example
1000 hp
2200 volts
600 rpm
Ri = 0.9
for ki = 0.0002
Fig. 11.


Armature winding insulation resistance of direct current motors and generators
Use 100 kw for machines less than 100 kw rating
$R_i = k_d \dfrac{(\text{Voltage} + 1400)\ \text{rpm}^{\frac{1}{2}}}{\text{kw}^{\frac{1}{3}}}$ (megohms)
Voltage
3000
2500
2000
1500
1000
500
100
Machine condition
Winding temperature
k_d
New
21°C
0.02 to 0.1
Good operation
21°C
0.01
Minimum
75°C
0.0001
Kw
10000
5000
4000
3000
2000
1000
500
400
300
200
100
k_d
0.1
0.05
0.04
0.03
0.02
0.01
0.005
0.004
0.003
0.002
0.001
0.0005
0.0004
0.0003
0.0002
0.0001
Minimum
R_i
5000
4000
3000
2000
1000
500
400
300
200
100
50
40
30
20
10
5
4
3
2
1
0.5
0.4
0.3
0.2
0.1
0.05
0.04
0.03
Pivot line
Pivot line
Example
1000 kw
600 volts
900 rpm
R_i = 0.6
for k_s=0.0001
Rpm
4000
3000
2000
1500
1000
500
400
300
200
150
100
50
Fig. 12.


Armature winding insulation resistance of synchronous converters
Use 100 kw for machines less than 100 kw rating
$R_i = k_c \dfrac{(\text{voltage} + 1000)\ \text{rpm}^{\frac{1}{2}}}{\text{kw}^{\frac{1}{4}}}$ (megohms)
Voltage
1500
1000
500
100
Machine condition
New
Good operation
Minimum
Winding temperature
21°C
21°C
75°C
k_c
0.02 to 0.1
0.008
0.00007
Pivot line
R_i
3000
2000
1000
500
400
300
200
100
50
40
30
20
10
5
4
3
2
1
0.5
0.4
0.3
0.2
0.1
0.05
0.04
0.03
0.02
0.01
Pivot line
k_c
0.1
0.05
0.04
0.03
0.02
0.01
0.005
0.004
0.003
0.002
0.001
0.0005
0.0004
0.0003
0.0002
0.0001
Minimum
0.00007
Kw
10000
5000
3000
2000
1000
500
100
Example
1000 kw
600 volts
900 rpm
$R_i = 0.6$
for $k_c = 0.00007$
Rpm
1500
1000
500
400
300
200
100
Fig. 13.

News

Of Institute and Related Activities

Summary Convention to Be Held This Month at Hot Springs, Va.

ALL is in readiness for the fiftieth annual summer convention of the A.I.E.E., which will be held in Hot Springs, Va., June 25–29, 1934, with headquarters in The Homestead. The summer convention committee, under the chairmanship of W. S. Rodman, has arranged an excellent schedule of events. The annual business meeting and the technical sessions will be held during the mornings so that the afternoons are free for sports and recreation. In the evenings, the president's reception, a get-together banquet with entertainment, and the convention banquet will be held and followed by dancing.

One of the features of the convention will be the commemoration of the fiftieth anniversary of the Institute and special addresses by Dr. W. E. Wickenden and Dr. William McClellan. The commemoration ceremonies will take place following the annual business meeting on Monday morning and it is hoped that all officers of the Institute, all living past-presidents, and all living charter members, as well as a goodly representation of engineers from all sections will be present. Another feature will be the conference of officers, delegates, and members which will be held on Monday and Tuesday afternoons. To complete the professional activities a technical program has been scheduled during the remainder of the week, which consists of 7 sessions: education, electrical machinery, communication, insulators, automatic stations, power generation, and instruments and measurements. The papers for these sessions appear in this issue except 3 which have been previously published in ELECTRICAL ENGINEERING: "Iron Shielding for Telephone Cables" by H. R. Moore, Feb., p. 274–80; "Recent Developments in Power Line Carrier" by T. Johnson, Jr., April, p. 542–7, and "Industry Demands and Engineering Education" by L. W. W. Morrow, April, p. 518–22. Pamphlet copies are not available and members should take these issues with them to the convention.

The complete program and other pertinent information relative to hotel rates, and reduced railroad rates, was given in ELECTRICAL ENGINEERING for May, p. 842–4. Complete your plans now to attend this fiftieth annual summer convention at Hot Springs, Va. Members in the nearby districts who have received mail registration cards should fill in and post them promptly.

A green on the golf course of The Homestead, Hot Springs, Va. This course, at an elevation of 2,300 ft, may be played by members attending the Institute's 50th annual summer convention at Hot Springs, June 25–29, 1934

Annual Reports to Be Made Available

The annual reports of those technical committees of the Institute which are compiling reports for the past year are scheduled for publication in the July issue of ELECTRICAL ENGINEERING. The heavy demand for space in the June issue made by the papers to be discussed at the Institute's summer convention, Hot Springs, Va., June 25–29, 1934, and the lateness of a few of the technical committee reports, precluded complete publication of the reports in this issue. All reports which are being made available by the technical committees therefore are scheduled for inclusion in the next issue.

The annual report of the board of directors is also scheduled for publication in the July issue of ELECTRICAL ENGINEERING. This report will be officially presented at the Institute's summer convention at Hot Springs.

The annual reports on Section and Branch activities for 1933–34 are given on accompanying pages of the news section of the present issue, as is the report on award of Institute prizes for papers presented in 1933.

Pacific Coast Convention Plans Being Made

Salt Lake City, Utah, will be host to the 1934 Pacific Coast convention, September 3–7, 1934. Convention headquarters will be in the Hotel Utah.

The general convention committee is arranging a most attractive program of broad appeal. Five technical sessions have been tentatively arranged as follows: communication, management and selected subjects, lightning, power transmission and stability, and protective devices. With the exception of one session on Monday afternoon, these sessions will be scheduled in the mornings, which will leave the other afternoons open for inspection trips, recreation, and entertainment features. Two student sessions will be held in addition to the 5 technical sessions.

Salt Lake City is centrally located in America's vacation grounds. Yellowstone National Park is but a night's ride to the north, while the Grand Canyon, Zion National Park, and Bryce Canyon are within a night's ride to the south. Also the Boulder Dam construction will be, during the present summer and fall, at its most interesting stage. Arrange your vacation plans so as to attend the Pacific Coast convention at Salt Lake City, September 3–7, and take advantage of the unusual opportunities which its natural location affords.

1934 Lamme Medal Nominations Due Nov. 1

Special attention is directed to the fact that the names of Institute members who are considered eligible for the Lamme Medal, to be awarded in the fall of 1934, may be submitted by any member in accordance with Section 1 of Article VI of the by-laws of the Lamme Medal committee, as quoted in the following:

> The committee shall cause to be published in one or more issues of ELECTRICAL ENGINEERING, or of its successors, each year, preferably including the June issue, a statement regarding the "Lamme Medal" and an invitation for any member to pre-

sent to the national secretary of the Institute by November 1, the name of a member as a nominee for the medal, accompanied by a statement of his "meritorious achievement" and the names of at least 3 engineers of standing who are familiar with the achievement.

Each nomination should give concisely the specific grounds upon which the award is proposed, and also a complete detailed statement of the achievements of the nominee to enable the committee to determine its significance as compared with the achievements of other nominees. If the work of the nominee has been of a somewhat general character in coöperation with others, specific information should be given regarding his individual contributions. Names of endorsers should be given as specified above.

The Lamme Medal, founded as a result of a bequest of the late Benjamin Garver Lamme, chief engineer of the Westinghouse Electric and Manufacturing Company (deceased July 8, 1924), provides for the annual award by the Institute of a gold medal —together with bronze replica thereof— to a member of the A.I.E.E. "who has shown meritorious achievement in the development of electrical apparatus or machinery"; and for the award of 2 such medals in some years if the accumulation of funds warrants.

The sixth (1933) Lamme Medal has been awarded to Lewis B. Stillwell (A'92, M'92, F'12, member for life and past-president) consulting engineer, New York, N. Y., "for his distinguished career in connection with the design, installation, and operation of electrical machinery and equipment." Presentation will be made during the summer convention at Hot Springs, Va., June 25–29, 1934.

North Eastern District Holds Tenth Annual Meeting at Worcester, Mass.

THE Worcester Section played host to those who attended the tenth annual meeting of the Institute's North Eastern District in Worcester, Mass., May 16–18, inclusive. The official registration was 337, including more than 100 Enrolled Students.

The District meeting idea was pioneered by the North Eastern District in 1924 as a major contribution toward the Institute's effort so to decentralize and distribute its major activities as to make them more available to the membership. From its New England birthplace, the District meeting idea spread to several other Districts with excellent results. Further pioneering was undertaken by that District in 1932 when, in connection with its Providence meeting, the then prevalent tradition of having pamphlet copies of all technical papers available for general distribution was, in the interest of economy, dispensed with successfully. Still further pioneering was undertaken by the District this year when, in spite of the fact that no appropriation for a North Eastern District meeting was included in the national budget for 1933–34, the District decided to hold the Worcester meeting "on its own," with the coöperation and support of national headquarters, but without any expense to the Institute as a whole. The result reflects credit upon those who conceived the idea and upon those who carried it through to its successful conclusion.

Of course, the Institute's new unified publication plan contributed its part to the foundation underlying the success of the technical sessions. Except for a few special papers of particular local interest, the program committee was able to select most of the papers for discussion from among those that had been published in ELECTRICAL ENGINEERING in advance of the meeting and thus distributed to the entire membership of the Institute. This arrangement obviated the publication expense usually involved in a meeting, as well as providing an opportunity for broader discussion of the technical papers. A desirable simplicity in the entertainment and other special features of the meeting program, together with the coöperation of the various committees that handled the details, contributed toward reducing the meeting expense to a point where it constituted only a very nominal drain on the District's treasury (all Sections in the District contribute proportionately toward joint District activities).

Except for minor modifications the program for the 4 general sessions and for the student session was carried out as published previously in ELECTRICAL ENGINEERING. Louis S. Leavitt, local general chairman, presided at the opening session, which was made very brief in order to give maximum time to the first technical session that followed immediately. Chairman Leavitt and District Vice-President J. Allen Johnson both spoke briefly in welcome to those attending.

The usual general session convened the second morning featuring the addresses of Past-President Charles F. Scott, and Presidential Nominee J. Allen Johnson. Doctor Scott presented a brief and interesting résumé of the Institute's 50 years of history, outlining some of the material covered in his article in the May issue of ELECTRICAL ENGINEERING, and inspiring those present to continue the successful development of the Institute. J. Allen Johnson in his address spoke at some length on "An Insight Into the Workings of the A.I.E.E.," in which he described and explained many of the more important phases of the Institute's work and of its functioning as a national organization. He summed up his address by stating that the Institute's "Aims and activities are routed in a spirit of mutual helpfulness . . . and disinterested service to humanity . . . the principal obligation of membership . . . is to cultivate that spirit, the possession of which, after all is said and done, yields the most lasting satisfactions in the professional life." Mr. Johnson's address is scheduled for publication in an early issue of ELECTRICAL ENGINEERING; time and space available precluded its inclusion in this issue.

Chairmen presiding at the various technical sessions were: Wednesday morning, Prof. T. H. Morgan of Worcester Polytechnic Institute; Wednesday afternoon, I. E. Moultrop, Boston, past vice-president; Thursday morning, Louis F. Leavitt, chairman of the Worcester Section; Friday morning student session, Prof. L. W. Hitchcock, University of New Hampshire, Durham, N.H.; Friday afternoon, C. A. M. Weber, Westinghouse Elec. and Mfg. Company, Springfield, Mass. Sessions Wednesday and Thursday were held in the Ball Room of the Bancroft Hotel, Friday at Worcester Polytechnic Institute.

STUDENT SESSION

Upholding the North Eastern District's tradition, the Friday morning student session, held in a lecture hall at Worcester Polytechnic Institute, was one of the liveliest and best attended of all the sessions. The student papers presented included:

1. TELEVISION, Gordon K. Burns, Massachusetts Institute of Technology.

2. SOLVING THE CONDENSER MICROPHONE EQUATIONS, R. B. Gray, Cornell University.

3. STUDY OF PHASE SHIFT OF ISOCHRONOUS BROADCAST STATIONS, J. B. Campbell, Worcester Polytechnic Institute.

4. LIGHTNING EFFECTS, D. D. Terwilliger, Massachusetts Institute of Technology.

Cloth Bound Copies of 50th Anniversary Issue

Numerous inquiries have been received with reference to the possible availability of cloth bound copies of the special May 1934 issue of ELECTRICAL ENGINEERING, which commemorated the 50th anniversary of the founding of the Institute. On the strength of these inquiries, several hundred sets of forms have been printed and laid aside pending a determination of just how many may wish to procure cloth bound copies of that issue.

To the extent that bound copies are to be issued, it is contemplated that these volumes will include the entire content of the issue including the covers. The price is $2.50 per copy, postage paid; no discounts to be allowed.

Any persons wishing to reserve a copy of this contemplated issue of bound volumes, should so inform the Order Department at Institute headquarters as early as possible. It is important to note that the stock, available for bound volumes is definitely limited, and that all orders will be filled in the order of their receipt up to the limit of the available stock. An allotment has been set aside to protect foreign orders received at Institute headquarters by September 15, 1934.

5. Applications of the Thyratron in Industry, Amos Kent and G. H. Durfee, Rhode Island State College.

6. The Place of Operational Calculus in Undergraduate Study of Electrical Engineering, A. E. French, Clarkson College of Technology.

7. Interesting Effects of Series Transformers With Capacitance Burdens, E. D. Bassett and F. M. Potter, Worcester Polytechnic Institute.

Attentiveness of the audience and extent of the discussion following presentation indicated the keen interest in each of these papers. As before, the North Eastern District had offered prizes on the basis of the content and clarity of the presentation and the personality and ability of the author to handle his subject. The competition was keen and the judges were faced with some difficulty in announcing their decision:

First, Gordon K. Burns, Massachusetts Institute of Technology, $10.

Second, J. B. Campbell, Worcester Polytechnic Institute, $5.

Third, A. E. French, Clarkson College of Technology, $3.

Graduate prize, F. M. Potter and E. D. Bassett, Worcester Polytechnic Institute, $10.

Entertainment and Special Features

Several definitely organized inspection trips and other opportunities for individual or small-party inspections were provided by the local committee. The largest crowd, 100 or more, spent an afternoon in the South Works of the American Steel and Wire Company where they were shown the spring mill, the cable works, the open hearth furnaces, the rolling mills, the automatic electric welding machines used in the manufacture of rail bonds, and the wire drawing mill. Other parties visited local plants and stations of the Worcester Electric Light Company, and nearby substations of the New England Power Association. Other technical inspection trips included the plant of the Norton Company, manufacturers of abrasive and grinding machinery; the Heald Machine Company, manufacturers of precision tools and automatic machinery, and the Worcester Pressed Steel Company. The John W. Higgins Armory, at the plant of the latter company, with its library, laboratory, and collection of representative pressed steel products, ancient and modern and collected from all parts of the world, proved to be of great interest to all who saw it. The exhibits ranged all the way from utensils of the stone age and of the bronze age, including Greek and Roman armor, through the early iron age, the era of the Crusader's armor, and on to the modern steel age where one of the most striking exhibits was an aeroplane crankshaft and mountings in polished steel that emphasized the symmetry and simple beauty of thoughtful modern design.

Trips and activities arranged especially for the women guests included the Worcester Art Museum, a tea in the home of Mrs. Albert S. Richey, who headed the local women's committee, luncheon and bridge at the Worcester Country Club, an automobile trip to the summit of Mt. Wachusett, and an inspection and tea at the John W. Higgins Armory.

General activities included an informal entertainment held Wednesday evening, at which representatives of the General Electric Company presented a colorful exhibition of remote (vacuum tube) control and blending of stage and other color lighting effects, and representatives of the Westinghouse company presented a demonstration reflecting modern possibilities in control apparatus, by means of which it was possible to start, stop, and reverse an electric motor by means of voice impulses variously translated through sound- and light-sensitive devices. One of the principal features of the entertainment was the Worcester Polytechnic Institute's male quartet which responded to numerous encores.

With Thursday night open for various informal affairs, the District meeting was brought officially to a close by the traditional annual dinner meeting held Friday evening in the dining room of the Sanford Riley Dormitory at Worcester Polytechnic Institute. This gathering of more than 125 was presided over by Vice-President J. Allen Johnson and was addressed by Rear Admiral Ralph Earle, president of the Worcester Polytechnic Institute, and F. M. Feiker, executive secretary of the American Engineering Council, Washington, D. C. Rear Admiral Earle recalled his early days as a midshipman, before the day of the alternator, and mentioned briefly a few of his experiences as an early naval instructor in electrical subjects, and his World War service in the naval ordnance department where, he said, war demands contributed definitely to the ultimate perfection of the modern synchronous motor. Mr. Feiker outlined briefly the history of American Engineering Council, and emphasized its several important possibilities as the "Washington embassy of the engineering societies." National Secretary H. H. Henline responded briefly to the chairman's laudatory introduction. Prof. W. H. Timbie of Massachusetts Institute of Technology, the North Eastern District's vice-presidential nominee, spoke briefly of the Institute's long leadership in electrical matters, including education, and of the inspiration that can be derived by active and constructive participation in Institute affairs.

District Secretary-Treasurer A. C. Stevens presented the citations and prize awards for 1933 papers from the District:

1. Student Branch prize—Awarded jointly to H. L. Anderson and E. L. Angell for their paper "A Study of Mercury Switches."

2. District first-paper prize—to R. F. Edgar of Schenectady, N. Y., for his paper "Loss Characteristics of Silicon Steel."

3. District best-paper prize—Jointly to C. L. Dawes of Harvard University and P. H. Humphries, now of Tulane University, for their paper "The Electrical Characteristics of Impregnated Cable Papers."

4. Honorable mention—D. W. McLenegan of Schenectady, N. Y., for his paper "Energy Requirements of Various Types of Air Conditioning Apparatus."

5. Honorable mention—J. Allen Johnson, Buffalo, N. Y., for his paper "Operating Aspects of Reactive Power."

All of these papers were presented at the North Eastern District ninth annual meeting held at Schenectady, N. Y., May 10–12, 1933.

A special feature following the annual dinner Friday evening was an illustrated semi-popular lecture delivered most effectively by Dr. Robert J. Van De Graaff of Massachusetts Institute of Technology on the subject "High Voltage and Its Application to Atomic Disintegration." In his lecture Doctor Van De Graaff explained the essential features of the modern understanding of atomic structure and mentioned briefly the efforts currently being made to

A Warning Against Fraud

Attention of Institute headquarters has been called to the activities of an individual who has requested employment and financial assistance in different parts of the country, and has defrauded those who helped him. This man usually claims to be Ralph E. Adams, a graduate of either Massachusetts Institute of Technology or of Yale University in the class of 1904, and to have taken graduate work at Stanford University, Glasgow University, and in universities in Germany and Spain. He is a short, thick set, stocky man, height 5 ft. 8½ in., weight 182 lb., about 52 years of age. His hair is silver-grey; he is well dressed, neat in appearance, with well kept hands. He gives every evidence of acceptable social refinement, and is an entertaining talker.

He apparently has done work in the examination of oil leases, and has had some experience in physical and chemical investigations. He frequently claims that his clothes, possessions, money, and automobile have been stolen from him by riders to whom he has given a "lift," and that he is in need of a loan to cover living expenses for a few weeks until he has become oriented on a new position which has been offered him in another city.

Since this man may try the same game elsewhere, members should be on the watch for him. The police are now in search of this imposter, and warrants will be issued immediately upon locating him.

Attention should also be given the fact that during recent months a number of instances has come to light of persons claiming past or present Institute membership when applying for jobs or for assistance. To guard against possible misrepresentation, it is recommended that inquiries covering all items of this character be sent promptly to Institute headquarters to be checked.

Future AIEE Meetings

Summer Convention,
Hot Springs, Va., June 25–29, 1934

Pacific Coast Convention,
Salt Lake City, Utah, Sept. 3–7, 1934

carry researches in this subject further by means of the tremendously high impulse voltages now possible in the laboratory through the "static" type of generator originally devised by Doctor Van De Graaff. The speaker then described the principal features of this special device which in its original form was a classroom model capable of developing several thousand volts, and which now is being built on such a scale that it requires an airship hangar to accommodate it, and is capable of developing several million volts.

Registration

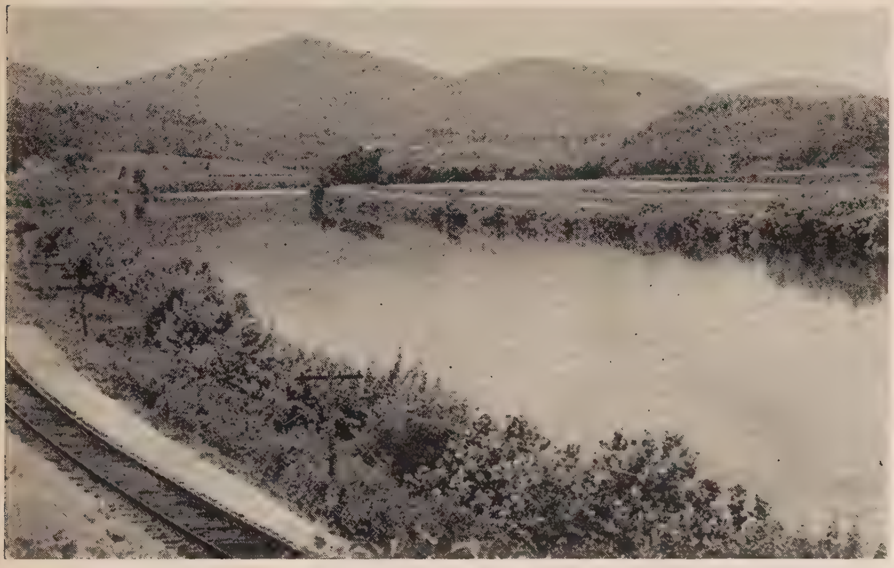
Attendance at all sessions was good. Analysis of final registration data showed:

Worcester Enrolled Students	63
Out-of-town Enrolled Students	79
Worcester Members and Guests	46
Out-of-town Members and Guests	130
Women Guests	19
Total	337

Registration personnel and facilities were provided through the coöperation of the publicity and convention bureau of the Worcester Chamber of Commerce.

Chemists' Medal to Be Presented Doctor Conant. The medal of The American Institute of Chemists, presented annually for outstanding service to chemistry in America, has been awarded this year to Dr. James Bryant Conant, president of Harvard University, in recognition of his many contributions to chemical science. Doctor Conant has done notable work in establishing the chemical structure of many complicated organic compounds, including, among others, haemoglobin of the blood substance, chlorophyll—the green coloring matter found in plant life, and a number of other coloring substances occurring in flowers and feathers. He has greatly extended the usefulness of electrometric methods, applying them to new problems, and has made many other fundamental researches. He has written 3 textbooks and many papers on subjects in organic chemistry. Doctor Conant became 25th president of Harvard University in May 1933, when he had just passed his 40th birthday. The presentation of the medal was made at the annual meeting of The American Institute of Chemists in New York, May 21, 1934.

A Few of Virginia's Many Natural Attractions Near Hot Springs



THOSE attending the Institute's fiftieth annual summer convention at Hot Springs by motor will have an excellent opportunity to see some of the underground caverns and other natural wonders for which the state of Virginia is noted. Above at the right is a view of the famous Natural Bridge a few miles southeast of Hot Springs. Hewn out of solid limestone by the waters of past ages this great natural arch stands more than 200 ft high and has a 90-ft span. Lee Highway (U.S. No. 11) passes over the top. At the right is a view of the "natural chimneys" near Mt. Solon, a few miles northeast of Hot Springs. Here 7 massive columns, 2 of which stand more than 100 ft high, have been eroded from the limestone cliff. Above is a typical view from the scenic highway (U.S. No. 60) along the James River between Lynchburg and Natural Bridge.

Institute Prize Awards Announced for 1933 Papers

FOUR national prizes for papers presented during the calendar year 1933 have been announced by the committee on award of Institute prizes, which consists of R. N. Conwell (A'15, F'31) *chairman*, F. M. Farmer (A'02, F'13), W. H. Harrison (A'20, F'31) and E. B. Meyer (A'05, F'27). These prizes in each case consist of a suitable certificate. Personal presentation of the prizes will take place at the opening session of the Institute's summer convention at Hot Springs, Va., June 25–29, 1934.

District prizes as announced by 3 Districts to date include 2 awards of $25 each, together with appropriate certificates. Where there is a joint authorship the cash awards are divided.

National Prizes

Best Papers

Prize for best paper in engineering practice was awarded to F. H. Gulliksen (A'29) for his paper "The Principle of Condenser Discharge Applied to Central Station Control Problems," presented at the winter Convention, New York, N. Y., January 23–27, 1933.

Honorable mention was made of the following paper: "Operating Aspects of Reactive Power" by J. Allen Johnson (A'07, F'27), presented at the North Eastern District meeting, Schenectady, N. Y., May 10–12, 1933.

Prize for best paper in theory and research awarded to Joseph Slepian (A'17, F'27) and L. R. Ludwig (A'28) for their paper "A New Method for Initiating the Cathode of an Arc," presented at the winter convention, New York, N. Y., January 23–27, 1933.

Honorable mention was made of the following papers: "Applications of Harmonic Commutation for Thyratron Inverters and Rectifiers" by C. H. Willis (A'22, M'28), presented at the winter convention, New York, N. Y., January 23–27, 1933; and "Carrier in Cable" by A. B. Clark (M'19, F'30) and B. W. Kendall (M'18, F'29), presented at the summer convention, Chicago, Ill., June 26–30, 1933.

No prize was awarded in the field of public relations and education.

Initial Paper

Prize for initial paper was awarded to K. S. Wyatt (A'32), E. W. Spring (A'26, M'32), and C. H. Fellows for their paper "A New Method of Investigating Cable Deterioration and Its Application to Service Aged Cable," presented at the summer convention, Chicago, Ill., June 26–30, 1933.

Honorable mention was made of the following paper: "Compensating Metering in Theory and Practice" by George B. Schleicher (A'20), presented at the summer convention, Chicago, Ill., June 26–30, 1933.

Branch Paper

Prize for branch paper awarded to Tom B. Wagner for his paper "A Universal Measuring Instrument for Communication Circuits," presented at a joint meeting of the Portland Section and Oregon State College Branch, May 20, 1933.

Honorable mention was made of the following paper: "The Measurement and Control of the Synchronous Machine Torque Angle" by A. E. Logan and S. W. Hannah, presented at a joint meeting of the Denver Section and University of Colorado Branch, April 28, 1933.

District Prizes

District No. 1

Prize for best paper awarded jointly to C. L. Dawes (A'12, M'15) and P. H. Humphries (A'26) for their paper "The Electrical Characteristics of Impregnated Cable Papers," presented at the North Eastern District meeting, Schenectady, N. Y., May 10–12, 1933.

Prize for initial paper awarded to R. F. Edgar for his paper "Loss Characteristics of Silicon Steel at 60 Cycles with D-C Excitation," presented at the North Eastern District meeting, Schenectady, N. Y., May 10–12, 1933.

Prize for branch paper awarded jointly to H. L. Anderson and E. L. Angell for their paper "A Study of Mercury Switches," presented at the North Eastern District Meeting, Schenectady, N. Y., May 10–12, 1933.

District No. 7

Prize for branch paper awarded to C. Forest Himes for his paper "Aviation Radio," presented at a meeting of the Oklahoma Agricultural and Mechanical College Branch on April 10, 1933.

District No. 10

Prize for best paper awarded to W. J. Moulton-Redwood (A'20) for his paper "Valuation and Depreciation," presented at a meeting of the Toronto Section, October 27, 1933.

Prize for initial paper awarded to George Morrison (A'19) for his paper "Electrically Operated Mine Hoists," presented at a meeting of the Toronto Section, October 13, 1933.

Names Requested for Washington Award

The commission of the Washington Award requests that members of the 4 national societies of civil, mechanical, mining and metallurgical, and electrical engineers suggest the names to this commission of persons to be put on the list of those eligible to receive the Washington Award.

The commission of the Washington Award was established in 1917 by Past-President Alvord of the Western Society of Engineers "to be presented annually to an engineer whose work in some special instance, or whose services in general, have been noteworthy for their merit in promoting the public good." The award is made annually by a committee composed of 9 representatives of the Western Society of Engineers and 2 each from the A.S.C.E., A.I.M.E., A.S.M.E., and the A.I.E.E.

Suggestions should be made directly to Edgar S. Nethercut, director of the Western Society of Engineers, Chicago, Ill.

Triennial Montefiore Prize Award Now Open

Constituting interest on 150,000 Belgian francs, distributed triennially in international competition for the best original work presented on scientific advancement and progress in technical application of electricity in every field, the Montefiore prize award now is open again to candidates.

To be eligible an achievement must have been made public at some time during the three years immediately preceding the period of award. Papers either signed or anonymous are acceptable in manuscript or reprint form; they must, however, have been edited in either French or English; also, all manuscripts must be typewritten.

By a $^4/_6$ vote of the board of examiners composed of 5 Belgian and 5 other electrical engineers, $^1/_3$ of the amount available may be designated as an unsecured loan to a person whose work does not fall completely within the ritual of the governing program but which demonstrates a new thought in connection with development of importance in the sphere of electricity.

A.S.M.E. to Hold Semi-Annual Meeting in June. The semi-annual meeting of The American Society of Mechanical Engineers will be held in Denver, Colo., June 25–28, 1934, with headquarters at the Cosmopolitan Hotel. Among the subjects which will be discussed are smoke problems, heat engineering, air conditioning, and recent developments in railroad trains. A series of lectures with motion pictures will be presented to give a very complete story of the remarkable work of Boulder Dam. An informal round-table discussion has been arranged by the management division on the subject of the decentralization of industry, with particular reference to its effect in the West. The N.R.A. also will come in for discussion. A semi-formal banquet is to be held on Tuesday evening, and a number of interesting inspection trips have been arranged.

A.S.T.M. To Hold Annual Meeting in June. The 37th annual meeting of the American Society for Testing Materials will be held at Atlantic City, N. J., June 25–29, 1934. At this meeting, some 46 reports on metals, cement and concrete, ceramics, masonry materials, standards, nomenclature and definitions, and miscellaneous subjects will be presented. Also, 46 technical papers are scheduled for presentation at this meeting. The annual address will be given by the president, T. R. Lawson, and the ninth Edgar Marburg lecture will be given by Sheppard T. Powell, consulting sanitary and chemical engineer of Baltimore. His subject will be "Water as an Engineering and Industrial Material."

American Physical Society Meetings. The 192nd regular meeting of the American Physical Society will be held in Berkeley, Calif., June 18–23, 1934, as a joint meeting with Section *B* of the American Association for the Advancement of Science. Tentative plans for the program consist of symposiums for Wednesday and Thursday, one dealing with nuclear physics and the other with the values of important physical constants. The sessions on Friday and Saturday are to be devoted to the usual program of 10-min contributed papers. Prof. R. W. Wood of The Johns Hopkins University, and vice-president of the Society, will deliver an address dealing with his device for using the grating in measuring the velocity of stars. The 193rd regular meeting of the American Physical Society will be held in Ann Arbor, Mich., June 29 and 30, 1934. The Society will be the guests of the Uni-

versity of Michigan. Tentative plans for the program consist of a special address by Prof. George Gamow of the Polytechnical Institute, Leningrad, Russia; a symposium on hyperfine structure, one-half day for the reading of 10-min contributed papers; an excursion to the Ford plant and to Ford's museum at Dearborn; and a picnic supper at a nearby lake.

Guggenheim Medal Awarded to Boeing. For "successful pioneering and achievement in aircraft manufacture and air transportation" the Daniel Guggenheim Medal was awarded to William E. Boeing of Seattle, Wash., chairman of the board of the United Aircraft and Transport Corporation, on May 3, 1934. Mr. Boeing is widely known for his development of airplanes for both commercial and military purposes. One of his first efforts was the construction of a flying boat which carried the first air mail transported on the American continent by a private contractor, and when the war emergency found the government in need of planes, the Boeing plant was ready to get into production promptly. Under Mr. Boeing's direction, his company has pioneered in many phases of aircraft development. The Guggenheim award is made annually, this year the award having been made by a board consisting of 8 members in the United States and 7 abroad.

Pioneer in Electrical Development Dies. George Huntington Barker, organizer of the West Side Lighting Company, which later developed into the Southern California Edison Company, died at Santa Monica, Calif., April 29, 1934. He was born in Brookfield, N. Y., and had been a state senator from Gloucester County, N. J., before moving to California in 1893. Mr. Barker was 77 years old.

Section and Branch Activities Summarized in Annual Report for 1933–34

FOLLOWING the plan established in 1933, of publishing the annual report on Section and Branch activities in ELECTRICAL ENGINEERING instead of in pamphlet form, the report for the fiscal year which ended April 30, 1934, is presented here. Similar information for the fiscal year which ended April 30, 1932, was published in ELECTRICAL ENGINEERING for October 1932, pages 738–40, and for the fiscal year ending April 30, 1933, in ELECTRICAL ENGINEERING for June 1933, pages 726–8.

The accompanying comprehensive summary constitutes a report upon the large and important division of Institute activities coming under the supervision of the Sections committee and the committee on Student Branches, the 2 committees being composed of the following personnel: Sections—I. M. Stein, *chairman*, L. A. Doggett, W. B. Kouwenhoven, Everett S. Lee, G. H. Quermann, J. J. Shoemaker, W. H. Timbie, and, *ex-officio*, the chairman of all Sections of the Institute. Student Branches L. A. Doggett, *chairman*, R. B. Bonney, F. O. McMillan, Charles F. Scott, W. H. Timbie, and, *ex-officio*, all Student Branch counselors.

Section Activities

During the fiscal year which ended April 30, 1933, every Section of the Institute reported one or more meetings, and in virtually all cases the amount of activity was normal. The total number of meetings for the year was only slightly below that for the preceding year. All of the special features developed in recent years and found to be effective were retained.

President Whitehead visited many of the Sections during the fiscal year and visited several others in May. On account of the postponement of the Pacific Coast convention from 1933 to 1934, he visited all of the Sections which coöperated in the preparations for and the conduct of that convention.

Special efforts were made by the Section membership committees in coöperation with the national membership committee to induce individuals who had been forced during recent years to relinquish their membership to apply for reinstatement and excellent results have been reported by the national membership committee.

The New Orleans Section was organized in January with the entire state of Louisiana as its territory, and its members have taken up the Section activities with enthusiasm. This brought the total number of Sections to 61.

Many of the Sections enthusiastically accepted the suggestion of the fiftieth anniversary committee that each Section and each Branch hold a meeting during May 1934 for observing the fiftieth Anniversary of the organization of the Institute and made extensive plans for such meetings.

Detailed information on Section meetings during the past year is given in Table I, and Table II contains a brief summary of these meetings for the last 3 fiscal years.

Branch Activities

Nearly all of the Branches carried on a normal amount of activity during the past fiscal year which was completed with a total number of meetings practically equal to that for the preceding year. The strong emphasis upon the importance of having talks by Students which has been pronounced during the past several years was retained with the result that the total number of talks by Students for the year which ended April 30, 1934, was slightly larger than that for the preceding year.

The counselor delegates attending the summer convention held in Chicago in June 1933, discussed a report presented by a sub-

Table I—Section Meetings Held During Year Ending April 30, 1934

Section	A.I.E.E. Members Aug. 1932	A.I.E.E. Members Aug. 1933	Meetings During Year: Number	Meetings During Year: Avg Attendance	Avg Attendance as Per Cent of Membership Aug 1933
Akron	84	63	7	60	95
Atlanta	86	65	1	25	38
Baltimore	197	157	8	121	77
Birmingham	30	19	3	848	446
Boston	456	377	8	133	35
Chicago	850	633	7	166	26
Power Group	..	..	3	79	..
Cincinnati	162	146	10	201	138
Cleveland	257	193	8	242	125
Columbus	73	55	7	73	133
Connecticut	254	238	7	198	83
Dallas	103	78	9	93	119
Denver	134	130	9	112	86
Detroit-Ann Arbor	268	226	10	170	75
Erie	65	51	4	457	895
Florida	48	41	2	323	788
Fort Wayne	71	53	9	66	125
Houston	56	53	7	85	160
Indianapolis-Laf	85	73	5	130	178
Iowa	58	55	5	38	69
Ithaca	42	41	2	43	105
Kansas City	165	138	9	101	73
Lehigh Valley	248	176	10	172	98
Los Angeles	413	349	9	140	40
Louisville	53	48	9	88	183
Lynn	122	104	13	554	533
Madison	60	59	6	52	88
Memphis	40	30	9	55	183
Mexico	74	61	9	50	82
Milwaukee	218	161	15	112	70
Minnesota	99	79	8	41	52
Montana	34	31	8	69	222
Nebraska	57	45	2	50	111
New Orleans*	..	32	2	31	97
New York	3,394	2,798	4	550	20
Communication Group	..	..	3	548	..
Illumination Group	..	..	3	167	..
Power Group	..	..	4	338	..
Transportation Group	..	..	3	300	..
Niagara Frontier	162	142	9	74	52
North Carolina	80	68	1	1,277	1,880
Oklahoma City	77	77	8	113	147
Philadelphia	678	529	7	165	31
Pittsburgh	572	409	7	134	33
Pittsfield	117	90	10	734	815
Portland	88	81	8	72	89
Providence	80	73	8	57	78
Rochester	87	64	10	111	173
St. Louis	227	195	7	162	93
San Antonio	54	40	8	36	90
San Francisco	435	379	8	130	34
Saskatchewan	36	31	7	20	65
Schenectady	424	335	11	192	57
Seattle	181	133	10	62	47
Sharon	75	50	9	119	238
Southern Virginia	79	72	3	116	161
Spokane	39	33	8	29	88
Springfield, Mass.	96	72	9	103	143
Syracuse	72	62	2	390	628
Toledo	83	61	11	109	179
Toronto	372	302	16	121	40
Urbana	38	34	4	101	297
Utah	53	44	9	42	95
Vancouver	85	77	9	50	65
Washington	181	155	8	122	79
Worcester	65	65	8	266	409
Total...61	12,892	10,531			

Total number of meetings.............472
Total attendance..................73,271

*Authorized by executive committee: December 8, 1933.

committee of the committee on Student Branches, and recommended that provisions be adopted for enrollment in the Institute of evening students in electrical engi-

neering in institutions offering evening courses which are considered by the committee on Student Branches to meet the requirements outlined in the by-laws. They also recommended the adoption of provisions for the organization of such evening students for activities in connection with the corresponding Student Branches, each such case being subject to the approval of the committee on Student Branches.

These recommendations were approved in principle by the conference of officers, delegates, and members, and by the board of directors, with the understanding that further details would be developed by the appropriate committees. Later the by-laws were amended to include these provisions, and the committee on Student Branches has approved the enrolment of evening students of the following institutions: Polytechnic Institute of Brooklyn, University of Cincinnati, Cooper Union, George Washington University, College of the City of New York, and New York University.

The board of directors restored to the budget provisions for the allowance for traveling expenses for annual District conferences on Student activities in all Districts having committees on Student activities.

Of the 919 enrolled students whose terms expired April 30, 1934, nearly 50 per cent applied for admission as Associates.

New Branches were organized during the year at the South Dakota State College, Brookings, So. Dakota; and Villanova College, Villanova, Pa., bringing the total number of Branches to 113.

As reported above, the fiftieth anniversary Committee suggested that each Section and each Branch hold a meeting during the month of May, 1934, for observing the fiftieth anniversary of the organization of the Institute. Many of the Branches have planned to carry out this suggestion.

Much information on Branch activities during the past fiscal year is given in Tables III to VII.

Section and Branch Joint Meetings

As in past years an important feature of both Section and Branch activities was the coöperaıion between the 2 types of groups

Table II—Section Meetings Held During Last 3 Fiscal Years

	Fiscal Year Ending April 30		
	1932	1933	1934
Number of Sections	60	60	61
Number of meetings held	497	498	472
Average number of meetings	8.3	8.3	7.7
Total attendance	105,325	73,806	73,271
Average attendance per meeting	212	148	156

Table III—Branch Meetings Held During Year Ending April 30, 1934

Branch	Meetings During Year: Number	Meetings During Year: Avg Attendance	Approx. No. of Talks by Students
Akron, University of			
Alabama Polytechnic Institute	3	27	
Alabama, University of	10	58	9
Arizona, University of	22	11	22
Arkansas, University of	15	29	43
Armour Institute of Technology	10	42	1
British Columbia, Univ. of	11	15	15
Brooklyn, Polytechnic Inst. of	5	42	6
Bucknell University	6	33	4
California, Institute of Tech	10	67	6
California, University of	17	43	1
Carnegie Institute of Tech	5	63	9
Case School of Applied Science	17	58	28
Catholic University of America	4	20	4
Cincinnati, University of	7	60	
Clarkson College of Tech	1	34	
Clemson Agricultural College	8	34	13
Colorado State Agri. College	12	13	5
Colorado, University of	11	50	4
Cooper Union	9	37	3
Cornell University	3	47	
Denver, University of	10	30	2
Detroit, University of	6	33	
Drexel Institute	9	17	7
Duke University	9	18	17
Florida, University of	14	66	5
George Washington University	2	14	1
Georgia School of Tech	3	38	
Harvard University	3	32	2
Idaho, University of	7	34	5
Illinois, University of	8	64	
Iowa State College	8	97	1
Iowa, University of	24	38	30
Kansas State College	13	66	3
Kansas, University of	10	66	
Kentucky, University of	5	77	
Lafayette College			
Lehigh University	7	55	6
Lewis Institute	5	93	
Louisiana State University	4	23	3
Louisville, University of	11	24	12
Maine, University of	4	28	
Marquette University	6	52	
Massachusetts Inst. of Tech	6	73	
Michigan Col. of Min. & Tech	9	38	2
Michigan State College	10	18	5
Michigan, University of	7	54	
Milwaukee School of Engg	8	52	
Minnesota, University of	9	91	5
Mississippi State College	6	21	6
Missouri School of Mines & Met	3	41	2
Missouri, University of	10	30	8
Montana State College	30	59	86
Nebraska, University of	13	43	4
Nevada, University of	5	41	
Newark College of Engineering	8	26	12
New Hampshire, University of	23	36	39
New Mexico, University of	7	23	2
New York, Col. of the City of	12	26	7
New York University	11	22	43
North Carolina State College	14	68	18
North Carolina, University of	5	30	6
North Dakota State College	10	24	9
North Dakota, University of	15	18	19
Northeastern University	6	30	2
Notre Dame, University of	14	106	21
Ohio Northern University	10	17	8
Ohio State University	11	40	3
Ohio University	3	20	
Oklahoma A. & M. College	14	48	11
Oklahoma, University of	7	36	4
Oregon State College	8	55	2
Pennsylvania State College	10	61	17
Pennsylvania, University of	7	17	1
Pittsburgh, University of	26	77	24
Porto Rico, University of	7	39	2
Pratt Institute	19	41	26
Princeton University	3	58	
Purdue University	9	148	
Rensselaer Polytechnic Inst	5	191	5
Rhode Island State College	12	25	12
Rice Institute	9	47	3
Rose Polytechnic Institute	1	25	
Rutgers University	9	13	9
Santa Clara, University of	3	32	
So. Carolina, University of	13	34	13
South Dakota State College*	6	22	3
So. Dakota State School of Mines	6	44	8
South Dakota, University of	3	8	
Southern California, Univ. of	12	28	3
Southern Methodist University	4	19	
Stanford University	16	30	6
Stevens Institute of Tech			
Swarthmore College	1	3	
Syracuse University	22	15	34
Tennessee, University of	8	19	6
Texas A. & M. College	2	60	
Texas Technological College	11	21	7
Texas, University of	5	25	
Utah, University of	14	30	3
Vermont, University of	17	19	11
Villanova College†	4	24	4
Virginia Military Institute	5	20	
Virginia Polytechnic Institute	27	35	73
Virginia, University of	8	20	5
Washington, State College of	10	41	3
Washington, University of	12	39	7
Washington University	8	24	3
West Virginia University	18	33	121
Wisconsin, University of	3	39	
Worcester Polytechnic Inst	4	54	4
Wyoming, University of	8	22	
Yale University			
Total	113		1.004

Total number of meetings............. 1,015
Total attendance..................... 41,772

Authorized by board of directors:
* May 22, 1933
† October 20, 1933

Table IV—Branch Meetings Held During Last 3 Fiscal Years

	Fiscal Year Ending April 30		
	1932	1933	1934
Number of Branches	109	111	113
Number of meetings held	1,135	1,026	1,015
Average number of meetings	10.4	9.3	9.0
Total attendance	54,197	59,439	41,772
Average attendance per meeting	48	58	41
Number of student talks	1,066	982	1,004

Table V—Comparison of Branch Activities by Districts

District	No. of Branches Jan. 1	Avg No. Meetings per Branch	Avg Attendance per Meeting	Approx. Avg No. Student Talks per Branch	No. Branches Reporting 8 or More Student Talks
1	13	8.2	45	8.4	4
2	20	7.5	34	11.9	6
3	9	8.9	27	12.0	4
4	17	9.0	36	10.9	7
5	16	8.6	62	4.1	2
6	10	9.4	27	5.4	3
7	14	8.4	38	6.1	3
8	7	12.2	36	5.4	1
9	6	13.5	43	17.7	1
10	1	11.0	15	15.0	1

Table VI—Conferences on Student Activities

District	Location	Date
1	Schenectady, N. Y. (North Eastern District Mtg.)	5/12/33
4	Raleigh, No. Carolina (No. Carolina State College)	1/12/34
6	Rapid City, So. Dakota (So. Dakota State School of Mines)	4/13/34

which is especially effective in giving the students knowledge of the types of work which they will do later, and also develops many helpful exchanges of experiences between the 2 groups. Some of the outstanding examples of such coöperation during the past year are listed in Table VIII.

Table VII—Student Conventions

Sponsored by District	Location	Date	No. of Student Papers
1	Schenectady, N. Y. (No. Eastern District Mtg.)	5/12/33	13
Mass. Inst. of Tech.	Cambridge, Mass.	12/9/33	3
4	No. Carolina State Col.	1/12/34	6
6	So. Dakota State School of Mines	4/13/34	6
New York Section	New York	4/18/34	4
Princeton University	Princeton, N. J.	4/30/34	7

Table VIII—Section or Joint Section and Branch Meetings With Active Student Participation

Sections	Schools	Date	Student Talks	Attendance
Cincinnati	Univ. of Cincinnati	5/11/33	8	70
Oklahoma City	Univ. of Oklahoma Oklahoma A. & M. College	5/19/33	6	100
Portland	Oregon State College	5/20/33	2	57
Utah	Univ. of Utah	5/22/33	2	45
Pittsburgh	Carnegie Inst. of Tech. Univ. of Pittsburgh West Virginia Univ.	1/ 9/34	6	112
No. Carolina	No. Carolina State College	1/12/34	6	194
Vancouver	Univ. of British Columbia	3/ 5/34	4	52
Minnesota	Univ. of Minnesota	3/ 7/34	4	
Houston	Rice Institute A. & M. College of Texas	3/24/34	2	72
Seattle	Univ. of Washington	4/17/34	3	70
Los Angeles	Calif. Inst. of Tech. Univ. of Southern Calif.	4/17/34	6	127
Louisville	Univ. of Louisville	4/29/34	3	67
Denver	Univ. of Colorado Univ. of Denver	4/20/34	2	58
San Francisco	Univ. of Calif. Univ. of Santa Clara Stanford Univ.	4/27/34	3	135
Spokane	Univ. of Idaho Washington State College	4/27/34	2	70

American Engineering Council

Legislation and Administrative Policy Affecting Engineers

THE IMPORTANCE to engineers of events taking place in Washington, and the part which American Engineering Council takes in guiding legislation in logical channels, are indicated by the following excerpts from the report of American Engineering Council dated April 18, 1934. Although the status of some of the bills has changed since this report was issued, it reflects the activity of Council in Washington. The report follows:

Three Public Works Bills

Three public works bills have been introduced this month (April). The LaFollette and Brunner bills (S. 3348 and H.R. 9151) provide 10 and 12 billion, respectively, for the purpose of carrying forward the program of public works inaugurated under the provisions of the National Industrial Recovery Act. The Ellenbogen bill, H.R. 8979, provides an additional appropriation of 2 billion for the construction of public works projects and $400,000,000 for Federal grants to the several States for construction and extension of highways. Col. Frank M. Gunby (A'10, M'14) chairman of Council's committee on administration of public works has these bills under consideration.

It is probable that the Administration bill, not yet introduced, will coördinate some of the items named in the above bills for a total additional appropriation of approximately 2 billions of dollars.

Regulation of Communications

Of the 3 bills introduced in recent weeks seeking the establishment of a commission on communications, 2 are now being actively considered in Congress. The Dill bill, S. 3285 is pending before the Senate Committee on Interstate Commerce and will probably be reported on Friday or Saturday of this week. Additional hearings are to be held on the Rayburn bill, H.R. 8301, by the House Committee on Interstate and Foreign Commerce.

Council's committee on communications is making a thorough study of both the Dill and the Rayburn bills.

Engineers' Relation to the Securities Act

Three bills have been introduced looking to the modification of the Securities Act of 1933. They are S. 3125 and H.R. 8836, identical bills, introduced by Senator Thomas of Utah and Representative Scrugham of Nevada, and S. 3301, introduced by Senator Hastings.

A small committee of 3 has been appointed in the House of Representatives to study modification of the Securities Act with the idea of recommending remedial legislation. The committee is composed of the Honorable Abe Murdock of Utah, chairman, Honorable Harry L. Englebright of California, and Honorable Compton I. White of Idaho.

Council is coöperating with the American Institute of Consulting Engineers in an effort to have the severity of the penalties demanded in the civil liabilities clause materially reduced.

Restoration of Research Funds for Irrigation

When the bill making appropriations for the Department of Agriculture for fiscal year ending June 30, 1935, was first drafted, the Bureau of the Budget eliminated an appropriation of $87,933, for farm irrigation investigations. The elimination of this item meant the practical discontinuance of the division of irrigation in the bureau of agricultural engineering.

Council, upon the request of several sections of the American Society of Civil Engineers, wrote to the committee on appropriations of the House, asking the restoration of this appropriation to the bill.

When the bill became law a few days ago, it contained an appropriation of $350,318.00 for the bureau of agricultural engineering; $87,933, although not so earmarked, is for the continuance of the farm irrigation research work.

Uniform Administration of Public Lands

Council has supported over a period of years the principles contained in H.R. 6462, the Taylor bill, which seeks to prevent injury to the public grazing lands by preventing over grazing and soil deterioration, providing for their orderly use, improvement and development, and the stabilization of the livestock industry, which is dependent upon the public range.

This legislation has passed the House of Representatives and is now pending before the Senate committee on public lands. Senator Wagner plans to hold hearings before reporting the bill to the Senate.

"Following the Flags" at Washington

THE NEED and opportunity for a voice for organized engineers and engineering in the nation's capitol, is visualized in the accompanying reproduction of a retouched airplane photograph. The original appeared in the *United States News* and is reproduced with its permission. The location of the office of American Engineering Council, the "Washington Embassy" of American engineers and engineering, has been added to the original photograph with the idea of giving to engineers unacquainted with the city of Washington, not only a picture of the number and variety of the present government agencies, but to emphasize that through membership in their local and national societies, which Council represents, they have a representative in these many activities. That engineers individually as well as collectively are playing a part in the present program, is indicated by the fact that in Washington alone there are about 2,900 engineer-trained men in the administrative bureaus and agencies, about 1,000 of whom are newly resident.

Washington is the home of several hundred permanent and emergency agencies of the Executive, Legislative and Judicial branches of the Federal Government. The list below includes all of the emergency organizations but only a few of the permanent units, such as Government departments.

Agencies marked with an asterisk indicate those created since March 4, 1933.

AAA*—Agricultural Adjustment Administration
AB—Archives Building
AVA—Administration of Vet's. Affairs
BB—Bureau of the Budget
BEP—Bureau of Engraving and Printing
BIR—Bureau of Internal Revenue
BPR—Bureau of Public Roads
CAB*—Consumers' Advisory Board
CC*—Consumers' Counsel
CCC*—Commodity Credit Corp.
CSB*—Central Statistical Board
CSC—Civil Service Commission
CWA*—Civil Works Administration
Dept. of A—Department of Agriculture
Dept. of C—Department of Commerce
Dept. of I—Department of Interior
Dept. of J—Department of Justice
Dept. of L—Department of Labor
Dept. of N—Department of Navy
Old PO Dept.—Old Post Office Department (present offices)
Depts. of SWN—Departments of State, War, and Navy
Dept. of T—Department of Treasury
Dept. of W—Department of War
DLB*—Deposit Liquidation Board
ECW*—Emergency Conservation Work. (Official name for Civilian Conservation Corps)
EHC*—Emergency Housing Corp.
EHFA*—Electric Home and Farm Authority
FACA*—Federal Alcohol Control Administration
F&DA—Food and Drug Admin.
FCA*—Farm Credit Administration
FCT*—Federal Coördinator of Transportation
FDIC*—Federal Deposit Insurance Corporation
FERA*—Federal Emergency Relief Administration
FESB—Federal Employment Stabilization Board
FFMC*—Federal Farm Mortgage Corporation
FHLB—Federal Home Loan Bank Bd.
FOCB—Federal Oil Conservation Bd.
FPC—Federal Power Commission
FRB—Federal Reserve Board
FRC—Federal Radio Commission
FSHC*—Federal Subsistence Homesteads Corporation
FSLA*—Federal Savings and Loan Associations
FSRC*—Federal Surplus Relief Corp.
FTC—Federal Trade Commission
GAO—General Accounting Office
GFA—Grain Futures Administration
HOLC*—Home Owners' Loan Corp
IAB*—Industrial Advisory Board
ICC (old)—Interstate Commerce Commission (present offices)
LAB*—Labor Advisory Board
L of C—Library of Congress
NCB*—National Compliance Board
NEC*—National Emergency Council
NLB*—National Labor Board
NM—National Museum
NPB*—National Planning Board
NRA*—National Recovery Admin.
NRRB*—National Recovery Review Board
O of E—Office of Education
PAB*—Petroleum Administration Bd.
PHS—Public Health Service
PIA*—Petroleum Industry Admin.
PSAC*—Non-member Preferred Stock Advisory Committee
PWA*—Public Works Administration
RFC—Reconstruction Finance Corp.
SAB*—Science Advisory Board
SES*—Soil Erosion Service
SI—Smithsonian Institution
SOB—Senate Office Building
TEC*—The Executive Council
TVA*—Tennessee Valley Authority
TVAC*—Tennessee Valley Associated Coöperatives
USES*—U. S. Employment Service
VB—Veterans' Bureau
WH—White House

Five Bills on Flood Control

Of the 30 or 40 bills which have been introduced during the 73rd Congress and referred to House committee on flood control, only 5 appear to be active. They are now under consideration by L. L. Hidinger, chairman of Council's committee on flood control.

Two of the bills, H.R. 5692 and H.R. 5910, introduced by Representative Wilson, chairman of the House committee on flood control, seek to amend the Flood Control Act of 1928; one, H.R. 6368, introduced by Mr. Marland, provides for the control of the flood waters of the Arkansas River. Of the 2 introduced by Mr. Disney, H.R. 7339 provides for flood control, irrigation, navigation, production of electric power, regulation of soil erosion, etc., in the areas drained by the Arkansas, Red and White Rivers; and H.R. 7548 provides for the control of flood waters in the State of Oklahoma in the watershed of the Arkansas and Red Rivers.

Council seeks, with the aid of its member-organizations, to protect the engineering soundness of flood control legislation enacted.

Financing Private Development Under R.F.C.

There have been considerably over a hundred bills introduced in the House of Representatives alone, proposing amendments to and extensions of the authority of the Reconstruction Finance Corporation. Many of these bills seek to give aid to private industry. The committee on banking and currency has given considerable study to these bills but because of the pressure of other legislation pending before the committee has been unable to determine what action to take concerning them.

Council is watching the legislation closely in order to be ready to take action should any bills be reported of particular interest to engineering and to engineers.

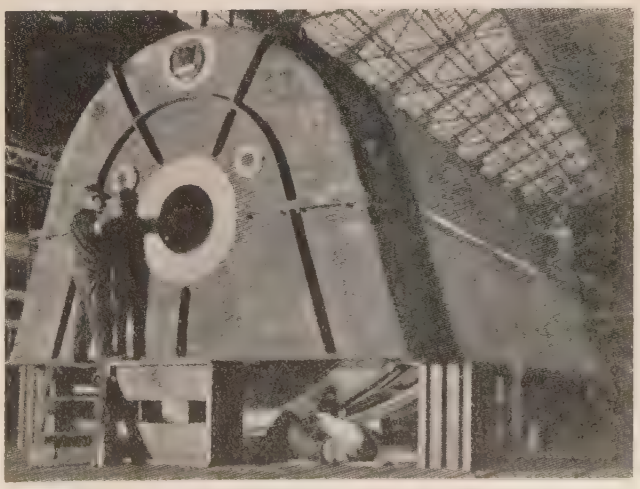
Salaries for Engineers

Engineers quite properly have thought of their income as based upon professional qualifications and not on hourly or weekly rates. Because of the demand for some standard of pay for different classes of work brought about by widely published discrepancies between wages paid for skilled and unskilled labor, and compensation for knowledge and supervising ability, effort has constantly been made by American Engineering Council to provide information to government agencies, particularly C.W.A and P.W.A., as to proper compensation for engineers. A special report on salaries was compiled by the American Society of Civil Engineers at the request of the C.W.A. and this has had a far-reaching and salutary effect in providing a basis for local determination of salaries and lifting the consideration of engineering salaries out of the class of hourly rates into the class of compensation for technical services and supervision. Council has distributed this report, on request, to several of the government agencies and also recommended the American Society of Mechanical Engineers' report on the "Economic Status of Engineers," to many in the government.

Mapping and Surveying the United States

To put the former C.W.A. project, supervised by the Coast and Geodetic Survey, on a sound national basis for continuation, the executive secretary of American Engineering Council, acting under earlier policies established by the Council, prepared with the coöperation of the United States Geological Survey and Coast and Geodetic Survey a memorandum, outlining the needs, proposing a plan and recommending an appropriation of $20,000,000 to provide in 2 years what would normally take 10 to accomplish—a basic map of the United States. The proposal has been agressively pushed and at present has the support of high government officials, of local, state and national organizations and of many members of Congress. It is hoped that the funds will be provided from the Public Works' Administration Bill for additional funds for the national recovery program. Not the least value in this project is that it will provide employment for between 8 and 10 thousand men during the next 2 years on a constructive need, which underlies both public and private development.

Building the Most Powerful Single-Shaft Generator



Building the stator frame for the world's most powerful single-shaft generating set in the East Pittsburgh, Pa., shops of the Westinghouse Electric and Manufacturing Company. Being built for the Richmond Generating plant of the Philadelphia Electric Company on the Delaware river at Philadelphia, the set will consist of a 183,333-kva 13,800-volt 3-phase 60-cycle 90-per cent power-factor generator driven by an 1,800-rpm turbine. Fabricated of welded steel plate and cast iron end bells it will weigh 215 tons with punchings, the frame alone weighing 65 tons. Because of its size, it will be shipped in 3 sections and the laminations will be stacked at the Richmond station.

Letters to the Editor

Slide Rule Calculation of Unbalanced 3-Phase Currents

To the Editor:

The author wishes to withdraw the solution for a-c circuits presented on p. 365 of the February 1934 issue of Electrical Engineering, since it has been found upon subsequent investigation, that eq 4 is not applicable as a general solution for unbalanced a-c circuits.

Very truly yours,

E. F. Seaman
(Assistant Electrical Engineer, Bureau of Engineering, Navy Dept., Washington, D. C.)

Appreciation of the "Science Series"

To the Editor:

We have been appreciative readers of the "Science Series for Engineers," being published in current issues of Electrical Engineering, and feel that articles of this nature are of considerable value in enabling practising electrical engineers to keep in touch with the advances of contemporary science.

We would suggest that consideration be given to the possibility of continuing this series indefinitely, rather than terminating it in January 1935, as mentioned in the February 1934 issue of Electrical Engineering.

Very truly yours,

C. L. Roach (A'24, M'30)
H. G. Palmer (A'30)
D. Rhodes (A'30)
(Div. Toll and Trmn. Engr., Engg. Asst., and Div. Trmn. Engr., respectively, of The Bell Telephone Co. of Canada, Montreal, Quebec)

Personal Items

J. B. Whitehead (A'00, F'12, and president) dean of the engineering school of the Johns Hopkins University, Baltimore, Maryland, has been awarded a medallion by the Advertising Club of that city for the work he performed last year in dielectric and capable research, considering it the year's most important contribution to the advancement of science made by a citizen of Baltimore.

C. E. Skinner (A'99, F'12, and junior past-president) formerly assistant director of engineering for the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa., and now retired, has been elected a vice-president of the American Association for the Advancement of Science and has been chosen chairman of its engineering section.

R. H. Barclay (A'14, F'28) has been made senior electrical engineer of the national power survey, which is a recently created branch of the Federal Power Commission. He will continue his connection for a while with McClelland Barclay Art Products, Inc., of which he has been president since 1931. Previously he had been with Stone and Webster.

O. M. Perry (A'14, M'25) manager, Windsor Hydro-Electric System, Windsor, Ont., Canada, was elected vice-president of the Association of Municipal Electrical Utilities, of Canada, at its recent convention at Toronto. He is also chairman of the convention committee for the year 1934 and a member of the rates committee.

W. P. Dobson (A'13, M'19) chief testing engineer, Hydro-Electric Power Commission of Ontario, Toronto, Ont., Canada, is a member of the papers committee of the Association of municipal Electrical Utilities, of Canada, serving for the year 1934. He is also a member of the regulations and standards committee.

E. R. Lawler (A'20) district electrical engineer for the Hydro-Electric Power Commission of Ontario was elected a member of the committee on accident prevention and health promotion of the Association of Municipal Electrical Utilities, of Canada, at its recent annual convention at Toronto.

T. C. James (A'18, M'18) district engineer for the Hydro-Electric Power Commission of Ontario was elected a member of the Committee on accident prevention and health promotion of the Association of Municipal Electrical Utilities, of Canada, at its recent annual convention at Toronto.

C. C. Curtis (A'23) has been selected as manager of the southwestern district of the Puget Sound Power and Light Company, at Olympia, Wash., succeeding A. M. Chitty (M'22). Mr. Curtis was division manager of the southern division at Olympia.

A. B. Cooper (A'16, F'33, and director) general manager and vice-president, Ferranti Electric Ltd., Mount Dennis, Toronto, Ont., Canada, has been appointed a member of the papers committee of the Association of Municipal Electrical Utilities, of Canada, to serve for the year 1934.

H. B. Dates (A'98, F'32) professor of electrical engineering at the Case School of Applied Science, Cleveland, Ohio, has been appointed administration member of the code authority for the vacuum cleaner manufacturing industry by the National Recovery Administration.

H. H. Weber (A'27, M'29) has been appointed assistant manager to C. W. Higbee, manager of tire sales, by the United States Rubber Products, Inc., New York, N. Y. Formerly he was director of low voltage engineering for the General Cable Corporation, New York City.

D. S. Jacobus (A'03) has been elected president of the American Welding Society. He has been associated with the Babcock and Wilcox Company since 1906 and at present is advisory engineer at the head of the engineering department. Doctor Jacobus devoted the earlier period of his life to teaching, joining the staff of the Stevens Institute of Technology after his graduation in 1884 and rising from the position of instructor in the department of experimental mechanics to that of professor of experimental mechanics and engineering physics. From 1900 to 1906 he was also in charge of the Carnegie Laboratory of Engineering. He is the author of numerous papers published in the transactions of various scientific and technical societies and engineering periodicals. He is a past-president of The American Society of Mechanical Engineers and of the American Society of Refrigerating Engineers, and a member of the American Institute of Mining Engineers, the Society for the Promotion of Engineering Education, and others.

D. S. JACOBUS

R. W. Atkinson (A'09, F'28) director of high voltage research, General Cable Corporation, Perth Amboy, N. J., represents the Institute on the new sectional committee on electrical insulating materials of the American Standards Association, sponsored by the American Society for Testing Materials.

Wills Maclachlan (A'08, F'21) consulting engineer of Toronto, Canada, was elected to membership on the committee on accident prevention and health promotion of the Association of Municipal Electrical Utilities, of Canada, at its recent annual convention.

Dean Harvey (A'04, M'13) electrical engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., represents the National Electrical Manufacturers Association on the new A.S.A. sectional committee on electric insulating materials.

M. S. Sloan (A'07, F'30) formerly president of the Brooklyn Edison Company has been named chairman of the board of the Missouri-Kansas-Texas Railroad. He became a member of the board a year ago and has been a member of the executive committee since that time.

Edgar Kobak (A'21, M'22) has been appointed vice-president in charge of sales of the National Broadcasting Company, New York, N. Y. He was formerly vice-president and general sales manager of the McGraw-Hill Publishing Company, New York, N. Y.

L. W. Going (A'19) chief electrical inspector for the City of Portland, Ore., is working with a committee of the Northwestern Electric Company and Portland General Electric Company to formulate a new set of rules for electric services and meters.

C. B. Martin (A'07) transmission engineer, New York Central Railroad Company, was elected vice-chairman of the new sectional committee on electrical insulating materials of the A.S.A.; he is a representative of the American Railway Association.

W. B. Kouwenhoven (A'06, F'34) professor of electrical engineering and assistant dean, Johns Hopkins University, Baltimore, Md., represents the Institute on the new sectional committee on electrical insulating materials of the A.S.A.

J. E. Teckoe (M'29) manager, Hydro-Electric Commission of Niagara Falls, Niagara Falls, Ont., Canada, is a member of the rates committee, for the year 1934, of the Association of Municipal Electrical Utilities, of Canada.

F. D. Weber (A'09, M'30) chief electrical engineer, Oregon Insurance Rating Bureau, is working with a committee of the Northwestern Electric and Portland General Electric companies to formulate a new set of rules for electric services and meters.

W. R. CHAWNER (A'26) has resigned his position as power sales engineer of the Southern Sierras Power Company at Riverside, Calif., which he held for 14 years, to become general manager of the Temescal Water Company, Corona, Calif.

J. D. ROSS (A'08, F'12) superintendent of lighting for the City of Seattle, Wash., has been called to Washington, D. C., on leave of absence, to assist in a nation-wide power survey which the Federal Trade Commission is conducting.

C. F. SCHMID (A'20, M'34) is now test engineer for the Kerite Insulated Wire and Cable Company, Seymour, Conn. He was formerly an engineer in the cable engineering department of the Anaconda Wire and Cable Company at Hastings-on-Hudson, N. Y.

H. W. HOUGH (A'08, M'13) has been elected vice-president and general manager of the Cleveland Electric Illuminating Company, Cleveland, Ohio. He has been associated with the company for 24 years and previously was associate general manager.

R. H. KNOWLTON (A'12) vice-president of The Connecticut Light and Power Company of Hartford, Conn., will act as vice-chairman of the New York–New England Regional Gas Sales Conference to be held at New London, Conn., in June 1934.

J. B. MCCARTHY (A'23, F'27) has been appointed vice-president in charge of sales of the Eugene F. Philips Electrical Works, Ltd., Montreal, Que., Canada. Previously he had been engineer, and assistant to the president.

G. W. HENYAM (A'20, M'26) commercial engineer, radio department, General Electric Company, Schenectady, N. Y., has been made chairman of a special section of radio applications of the National Electrical Manufacturers Association.

J. E. B. PHELPS (M'29) manager and electrical engineer, Sarnia Hydro Electric System, Sarnia, Ont., Canada, is a member of the merchandising committee, for the year 1934, of the Association of Municipal Electrical Utilities, of Canada.

A. G. OEHLER (A'18, F'28) editor of *Railway Electrical Engineer* and electrical department editor of *Railway Age*, New York, N. Y., has been elected to membership on the executive committee of the New York Section of the Institute.

M. F. SKINKER (A'22, M'27) assistant director of research, Brooklyn Edison Company, Brooklyn, N. Y., is a representative of the electric light and power group of the A.S.A. on its new sectional committee on electrical insulating materials.

H. S. VASSAR (A'06, M'18) laboratory engineer, Public Service Electric and Gas Company, Irvington, N. J., is a representative of the electric light and power group of the A.S.A. on its new sectional committee on electrical insulating materials.

ALLAN B. CAMPBELL (A'20, M'24) engineer, Edison Electric Institute, New York, N. Y., serves as alternate representative of the electric light and power group of the A.S.A. on its new sectional committee on electrical insulating materials.

J. M. WILSON (A'18) electrical engineer, Bell Telephone Laboratories, Inc., represents the American Society for Testing Materials on its new sectional committee on electrical insulating materials.

H. A. JOHNSON (M'17) general manager of the Chicago Rapid Transit Company, Chicago, Ill., has been elected a director of the company.

Obituary

EDSON OLIVER SESSIONS (A'02, M'07, F'13) president of the E. O. Sessions Co., Ltd., died on April 15, 1934, at Chicago. He was born in Louisville, Ky., December 23, 1871. He obtained his technical education by private study and at the École de Polytechnic in Paris, of which he was a graduate. He also took a student course at the Thomson-Houston Electric Company at Lynn, Mass. In 1889 he became assistant to the state suprintendent of construction, associated with the United Edison Manufacturing Company, and was engaged in the installation of lighting systems at Herkimer, N. Y., and at other locations throughout the state. In 1892 he was made general superintendent and engineer for the Northern Electrical Manufacturing Company at Concord, N. H., taking charge of the installation of many small, complete plants, steam, water and electric, in New Hampshire, Vermont, and Canada. In 1893, as superintendent and electrical engineer for the Frank Jones manufacturing interests, he built a complete monocyclic plant at Portsmouth, N. H., 2 d-c plants there, and installed plants at Sorrento, Me., and at Boston, Mass. In 1895 he was appointed general superintendent and took charge of all of the Frank Jones investigations, installing power plants in various parts of the world. In 1899 he was erecting engineer for the General Electric Company. In 1901 he became consulting engineer to W. S. Stratton of Colorado Springs, Colo., designing a complete power house for electric traction and planning improvements in his entire traction system. In 1902 he entered the employ of the Stanley Electric Manufacturing Company, as engineer of construction, installing several plants and substations. He became resident engineer in New York City for the Stanley concern later. In 1904 he was made western sales engineer of the Stanley organization with headquarters in Chicago. Since 1905 he had been engaged in an extensive consulting practice, at one time as a member of the firm of Woodmanese, Davidson and Sessions and later, from 1920 to 1928, as president and consulting engineer for the Sessions Engineering Company. In 1919 he was district manager of the U.S. shipping board. In 1931 he spent several months in Russia making a detailed engineering analysis of several projected Soviet industrial plants.

GEORGE HERBERT CONDICT (A'87, M'87) consulting electrical and mechanical engineer and inventor, of Plainfield, N. J., died April 9, 1934, at Orlando, Florida. He was born at Newark, N. J., in 1862. He graduated from the University of Pennsylvania. In 1882 he entered the employ of the Central Gas Light Company of San Francisco, and was connected with the building of gas plants in California and Oregon. In 1884 he became associated with the Pacific Coast Electric Construction Company of San Francisco, constructing dynamos and storage batteries. In 1885 he was the Pacific Coast agent for Van Depoele Electric Company of Chicago, erecting isolated arc and incandescent electric light plants in California. He visited Chicago and assisted Mr. Van Depoele in his electric railway and lighting experiments, installing his exhibition trolley line at the New Orleans Exposition in 1885. From 1887 to 1891 he was general manager of the Electric Car Company of America, at Philadelphia; 1892–93, chief engineer of the North American Storage Battery Company; 1893–96, sales engineer for the Electric Storage Battery Company of Philadelphia and San Francisco; 1896–97, general manager, Englewood and Chicago Railway; 1897–02, chief and consulting engineer, Electric Vehicle Company of New York and Hartford, Conn.; 1903–06, general manager, Electro-Dynamic Company of Philadelphia and New York; 1906–09, general manager, Box Electric Drill Company, New York; and 1909–12, manufacturers' sales engineer, New York and Jacksonville, Fla. From 1912 until his death he was engaged in an extensive consulting practice in the electrical and mechanical engineering fields. His inventions include the series parallel resistance controller, an improved storage battery for use as an auxiliary to provide for fluctuations of railway loads, and many other mechanical and electrical appliances and apparatus. During the War he was a member of the board of examiners for the Naval consulting board and from 1919 to 1920 he was on the technical advisory commission of the war claims board. He was a member of the Franklin Institute, the New York Electrical Society and the American Association for the Advancement of Science.

JAMES LYMAN (A'94, M'01, F'13, and Life Member) consulting engineer, retired, died from a heart attack on March 28, 1934, at Del Monte, Calif. He was born September 1, 1862, at Middlefield, Conn. He graduated from the Sheffield Scientific School of Yale University in 1883 with the degree of Ph.B. and from Cornell University in 1884 with the degree of M.E. In the latter year he became construction electrician for the Edison Construction Company and assisted in the installation of a number of lighting plants in Pennsylvania and one at Piqua, Ohio. From 1885 to 1886 he was assistant superintendent of

the Marr Construction Company which was organized to take over the construction work for the Edison company. He had entire charge of the installation of plants for the lighting companies at Johnstown, Wayne, Tamaqua, and DuBois, Pa., and also gave exhibitions of incandescent lighting. In 1886 he resigned his position with the Marr Construction Company to superintend the private interests of his family in the Metropolitan Manufacturing Company. In 1895 he received the degree M.M.E. from Cornell University and entered the employ of the General Electric Company as an assistant to Dr. C. P. Steinmetz. He conducted special experimental testing and designed various electric apparatus. About 3 years later he was transferred to the power and mining department. In 1899 he was appointed assistant engineer of the Chicago branch of the General Electric Company, and in 1911 was made district engineer for Chicago. From 1911 until his death he was associated with the firm of Sargent and Lundy, Inc., of Chicago, as electrical engineer, member, vice-president (1926–30), and as consultant retired, since 1930. He was a member of The American Society of Mechanical Engineers, American Electrochemical Society, Western Society of Engineers and the British Institution of Electrical Engineers.

George Johnson Newton (A'10, M'15) consulting engineer and specialist in designing and laying underground conduit and cable systems, died on March 26, 1934, at Sunland, Calif. He was born February 28, 1867, at Gloversville, N. Y. He attended the public schools of Tarrytown, N. Y., and obtained his technical education through his own efforts, studying and reading. For about 20 years he worked for various telephone companies, including the Westchester Telephone Company, Nyack, N. Y.; Metropolitan Telephone Company, New York City; New York and New Jersey Telephone Company; American Telephone and Telegraph Company at Syracuse; and Newark Telephone Company, Citizens Telephone Company, Kenosha, Wis. In 1904 he was engineer in charge of construction for the State Line Telephone Company, New York City. He was designing engineer with G. M. Gest in New York City from 1906 to 1916 when he established a consulting practice. From 1919 to 1922 he was designing engineer for the Connecticut Light and Power Company at Waterbury and in 1923 he was with the Philadelphia Electric Company. He resumed his practice as a consultant in 1924. He was one of the first engineers to realize the advantages of the 3-phase 4-wire system which he designed and installed at Dallas, Texas, Canton, Ohio, and at Denver, Colo. He designed similar systems for the British Columbia Electric Railway Company of Vancouver and for the American Gas and Electric Company at Atlantic City, which were installed later. He also designed and installed the 33,000-volt underground transmission system for the electrification of the Staten Island Rapid Transit. He served the Institute as a member of the transmission and distribution committee from 1916 to 1917 and from 1921 to 1924.

Herbert Eugene Kaighn (A'12, M'31) electrical engineer of Wilmington, Del., died on March 18, 1934. He was born August 19, 1875, at Washington, D. C. He secured his technical training through practice in and around the Navy Yard at Washington during his school day vacations and later through tutoring in electrical and mechanical engineering. He engaged in various branches of ordnance work. In 1898 he was an instructor in ordnance at the Naval Training Station, Newport, R. I. In 1899 he was in charge of electrical equipment, marine district, for the New York, New Haven and Hartford Railroad. From 1900 to 1904 he was ballistic engineer at the Naval Torpedo Station, Newport, R. I., and the following 2 years was inspector of ordnance and powder at the Philadelphia Navy Yard. In 1907 he entered the employ of the E. I. du Pont Company of Wilmington as ballisitic and experimental engineer in charge of installations, testing, designing and constructing electrical and physical apparatus for explosives tests. He left the E. I. du Pont Company in 1917 and established a consulting practice, specializing in designing and wiring hospital and institution systems until 1926, when he began specializing in radio and acoustic and amplifying systems. He was consultant for the American Car and Foundry Company on marine installations. He was a member of The American Society of Mechanical Engineers and the United States Naval Institute.

Guy Köchling Mitchell (A'06, M'14) engineer and appraiser and formerly president and proprietor of the Standard Electric Machinery Company of Baltimore, Md., died on January 15, 1934. He was born in Baltimore, July 5, 1877, and was educated at Baltimore Polytechnic Institute and through his own efforts. He worked for a year as draftsman and in the electrical shop of the United Electric Light and Power Company of Baltimore. In 1902, after a short period of work on the installation of a steam plant and transmission line for the Embree Iron Company of Embreeville, Tenn., he returned to Baltimore to do estimating and layout work in the distribution department of the United Electric Light and Power Company. In 1906 he went with Crook Horner Company as manager of the electrical department. When the firm dissolved in 1907 he purchased the electrical and elevator departments, and established the Standard Electric and Elevator Company, operating it as a manufacturing and contracting concern. Later it became the Standard Electric Machinery Company. He was the head of the company and in charge of all the engineering work for many years. During the war period he devised an automatic system for reconnection and rerating motors and generators of all makes and types, which filled a great many Government emergencies. He was a member of The American Society of Mechanical Engineers.

Charles Wilson Price (A'94, and member for life) who for many years was editor and owner of electrical publications, died in New York, N. Y., May 11, 1934. He was born at Barnesville, Ohio, in 1857. After learning the printing trade he became the editor of the *Barnesville Enterprise.* Going to Topeka, Kan., he was one of the founders in 1879, and for several years one of the editors of the *Topeka Daily Capital.* He later became interested in electrical science and in 1885 joined the staff of the *Electrical Review*, New York, of which he was for 37 years associate editor and editor-in-chief, and president of the Electrical Review Publishing Company. He purchased the *Western Electrician* in 1908, and *Electrocraft* in 1912, consolidating these with the *Electrical Review.* For a number of years preceding his death he was president of the Publishers Sales Company, Inc., and was a director in the Columbia Casualty Company, Commercial Union Fire Insurance Company, both of New York, N. Y., and was interested in Magazines, Inc., of Chicago. Mr. Price was a frequent contributor to newspapers and magazines on electrical subjects. He was a past-president of the Kansas Society of New York, and a member of the Ohio Society of New York, a past vice-president of the Lotus Club, and a member of the Press, Advertising, and Travel Clubs, all of New York. He was for several years secretary and treasurer of the International League Press Clubs.

Membership

Recommended for Transfer

The board of examiners, at its meeting held May 23, 1934, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

MacKavanagh, Thomas J., prof. of elec. engg., (Patent Attorney) The Catholic University of America, Washington, D. C.
Pilliod, James J., engr., long lines dept., American Tel. & Tel. Co., New York.
Vickers, Herbert, prof. and head of dept. of elec. & mech. engg., Univ. of British Columbia, Vancouver, B. C., Canada.

To Grade of Member

Belknap, J. Harrison, control engr., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Clement, Andrew E., member of technical staff, Bell Telephone Labs., Inc., New York.
Cogan, Charles M., secy. of the codes and standards committee, National Electrical Manufacturers Association, New York.
Cogswell, Burnham, field engr., General Electric Co., Buffalo, N. Y.
Cruikshank, James S., supt., elec. meter & installation Dept., Consolidated Gas Elec. Lt. & Pwr. Co., Baltimore, Md.
Dickinson, A. G., elec. engr., Consolidated Mining and Smelting Co., Trail, B. C., Canada.
Dunlop, Robert P., tests engr., Hong Kong Elec. Co., Ltd., North Point, Hong Kong, China.
Fetsch, Joseph T., Jr., asst. engr., radio, head of vacuum tube section at Naval Research Laboratory, Bellevue, D. C.
Gardner, John H., Jr., captain, signal corps, U.S. Army, Signal Corps Laboratories, Fort Monmouth, Oceanport, N. J.
Mathes, John A., foreman, test laboratory, United Elec. Lt. & Pwr. Co., New York.
Reed, Henry R., associate prof. of elec. engg., Michigan College of Mining and Technology, Houghton, Mich.
Russell, Chester, Jr., asst. prof. of elec. engg., University of New Mexico, Albuquerque, New Mexico.
Schramm, Frederic B., patent attorney, General Elec. Co., Schenectady, N. Y.
Smith, Edward F., asst. prof. of elec. engg., University of Florida, Gainesville, Fla.
Taylor, Paul B., 2123 California St., Washington, D. C.
Walker, Harry N., asst. prof. of elec. engg., New York University, New York.
White, Allen O., sales engr., General Elec. Co., Washington, D. C.
Wolff, Frank A., chief telephone section, Bureau of Standards, Washington, D. C.
Zubair, S. Mohammed, elec. engr., Buffalo, Niagara & Eastern Power Corp., Buffalo, N. Y.

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before June 30, 1934, or August 31, 1934, if the applicant resides outside of the United States or Canada.

Albright, C. L. (Member), Univ. of Richmond, Va.
Andry, P. L., Jr., Shell Petroleum Corp., Norco, La.
Antofilli, V., Nat. Dist. Tel. Co., Astoria, L. I., N. Y.
Baroco, J. F., Baroco Elec. Co., Pensacola, Fla.
Bethea, H. F., Graybar Elec. Co., Jacksonville, Fla.
Bialek, A. J., Duquesne Lt. Co., Pittsburgh, Pa.
Brown, W. E., Niagara Lockport & Ontario Pwr. Co., Olean, N. Y.
Callander, M. B., B. C. Elec. Ry. Co., Vancouver, B. C., Can.
Chinn, G. I., 1642 North Monroe St., Baltimore, Md.
Cook, R. K., Western Union Tel. Co., Phila., Pa.
Dadashev, M., Cornell Univ., Ithaca, N. Y.
Diehl, F. V., Okla. Gas & Elec. Co., Oklahoma City.
Elmore, D. R., Gibbs & Hill, Inc., N. Y. City.
Evans, O., 556 N. Getty St., Uvalde, Texas.
Ferguson, J. D., Ranier Natl. Park Co., Longmire, Wash.
Gehrmann, W. E., Am. Elevator & Machine Corp., N. Y. City.
Holder, DeW. H., Jr. (Member), Louisiana Pwr. & Lt. Co., Algiers.
Hollis, M. O., Jr., Raybro Elec. Supplies, Inc., Tampa, Fla.
Hoover, W. G., Stanford Univ., Stanford Univ., Calif.
Hutchinson, M. C., 128 E. 44 St., N. Y. City.
Johnson, E. W., Canada Wire & Cable Co., Ltd., Vancouver, B. C.
Kukutschka, E. (Member), AEG Cia. Mexicana de Electricidad S. A. Mexico, D. F., Mex.
Larsen, T., Bklyn. Edison Co., Inc., Bklyn., N. Y.
Lightbody, D. C., Hartford Steam Boiler Inspection & Ins. Co., Phila., Pa.
Martin, B. J., Bennett-Watts-Haywood Co., Chicago, Ill.
McGinity, J. V., Am. Steel & Wire Co., Tulsa, Okla.
McKnight, C. H., 1625 Vine St., Scranton, Pa.
Miller, H. E., Utilities Serv. Co., Allentown, Pa.
Milligan, H. F., Mountain States Tel. & Tel. Co., Santa Fe, New Mexico.
Morrison, W. G., Inland Engg. Co., Dallas, Texas.
Patton, G. M., P. McCuaig Ltd., Montreal, Que., Can.
Platt, A. B., Scranton Elec. Const. Co., Pa.
Poti, W. M., N. Y. & Queens Elec. Pwr. & Lt. Co., Flushing, N. Y.
Reisener, H. E., Westinghouse X-ray Co., Inc., Toledo, O.
Schweitzer, W. J., Jr., Detroit, Mich.
Smith, K. B., Carolina Pwr. & Lt. Co., Pee Dee, N. C.
Sparolini, J. A., Jr., Gen. Petroleum Corp., Monterey, Calif.
Wolfe, A. K., Allen Bradley Co., Milwaukee, Wis.

38 Domestic

Foreign

Chhabra, S. R., P. O. Kamabia, Distt. Lyallpur, Punjab, India.
Ewart, W. L. (Member), Lago Oil & Transport Co., Ltd., Aruba, Dutch West Indies.
Ghafoor, M. A., School for Electricians, Ludhiana, Punjab, India.
Green, R., Demerara Electric Co., Ltd., Demerara, British Guiana, S. A.
Pennell, E. R., Hewittic Elec. Co., Ltd., Thames, Eng.
Singh, G., Ganga Sugar Corp., Ltd., Saharanpur, U. P., India.

6 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Bonell, R. K., 45 Clifton St., Newark, N. J.
Brayman, Chas. E., c/o J. J. Murphy & Son, 38 Ford St., Hartford, Conn.
Chilberg, Ernest E., Gen. Elec. Co., 230 S. Clark St., Chicago, Ill.
Garvey, Fred A., 4144 Cottage Grove, Chicago, Ill.
Gilliam, Charles T., Power Cost Engg. Co., 742 Milam Bldg., San Antonio, Texas.
Goulding, Harold, 404 W. 116th St., New York, N. Y.
Gray, L. Tenney, Jr., 6452 Hillegas Ave., Oakland, Calif.
Hammond, William M., Idaho Springs, Colo.
MacDonald, Robert, 6 Rue Nicolas Charlet, Paris, France.
McNitt, Donald P., 1009 First Natl. Life Bldg., St. Louis, Mo.
Miller, Frank D., Box 34, Yatesboro, Pa.
Nemkowski, B., 104–25 115th St., Richmond Hill, N. Y.
O'Handley, Joseph A. E., 579—61st St., Bklyn., N. Y.
Patton, Edgar P., Standish Arms, 169 Columbia Heights, Bklyn., N. Y.
Tamburello, G., 307 West 20th St., N. Y. City.
Valier, Chas. E., Jr., 1804 Tel. Bldg., St. Louis, Mo.

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no resposibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

EASILY INTERPOLATED TRIGONOMETRIC TABLES with NON-INTERPOLATING LOGS, COLOGS and ANTILOGS. By F. W. Johnson. San Francisco, Simplified Series Pub. Co., 1933. Tables, 10x7 in., cloth, $3.50. Aims to provide logarithmic tables sufficiently accurate for ordinary calculations without any interpolation, and a set of trigonometric tables which can be interpolated more easily than others. The book contains both four-place and five-place tables of logarithms, cologarithms and antilogarithms, five-place tables of natural and logarithmic trigonometric functions, and various other tables, with instructions.

(The) ELECTROMAGNETIC FIELD. By H. F. Biggs. Oxford (England), Clarendon Press; N. Y., Oxford Univ. Press, 1934. 158 p., illus., 9x6 in., cloth, $3.50. Presents the classical theory of the electromagnetic field, for students of physics. Static fields, electrodynamics, Maxwell's equations, energy, momentum, and special relativity and the electromagnetic field are considered.

Great Britain. Dept. of Scientific and Industrial Research. REPORT for the Year 1932–1933. London, His Majesty's Stationery Office, 1934. 189 p., tables, 10x6 in., paper, 3s. (Obtainable from British Library of Information, N. Y., $0.88.) The work done by all the governmental research institutions and the licensed research associations is reviewed in this report, with lists of the publications that describe the results more fully.

HIGHER MATHEMATICS for ENGINEERS and PHYSICISTS. By I. S. and E. S. Sokolnikoff. N. Y. and Lond., McGraw-Hill Book Co., 1934. 482 p., illus., 9x6 in., cloth, $4.00. Aims to give students of engineering and other applied sciences a bird's-eye view of those topics of mathematics indispensable in the study of physical sciences, and thus to serve as a stepping-stone to advanced mathematical treatises.

INDUSTRIAL RADIOGRAPHY. By A. St. John and H. R. Isenburger. N. Y., John Wiley & Sons, 1934. 232 p., illus., tables, 9x6 in., cloth, $3.50. The general principles that govern the production and use of X rays and gamma rays are set forth clearly, together with the special technique suitable for important classes of materials. The equipment required and the methods of using it, and the radiography of large castings and forgings, of welded structures, and of small objects are discussed in practical fashion. Costs are considered briefly. There is a bibliography.

PRINCIPLES of RADIO. By K. Henney. 2 ed. N. Y., John Wiley & Sons, 1934. 491 p., illus., 8x5 in., cloth, $3.50. A practical presentation of the subject, which avoids the use of higher mathematics. The principles are presented simply, and their application to practical problems discussed. The book is well adapted to home study. This edition has been rewritten

Der KONDENSATOR in der STARKSTROMTECHNIK. By F. Bauer. Berlin, Julius Springer, 1934. 214 p., illus., 10x6 in., cloth, 18.50 rm. This work is chiefly concerned with questions relating to the use of condensers in factories and transmission systems. The general laws are presented briefly in an introductory chapter, and the greater portion of the book is devoted to the special technical and economic problems which arise in practice. A chapter upon design and construction is included.

Das LÄRMFREIE WOHNHAUS, herausgegeben von Fachausschuss für Lärmminderung beim Verein deutscher Ingenieure. Berlin, VDI-Verlag, 1934. 90 p., illus., 8x6 in., paper, 2.50 rm. Discusses the prevention and suppression of noise from the point of view of the builder and owner. The effect of noise upon human beings, methods of measurement, and practical methods for constructing soundproof buildings are described with sufficient detail. Issued by the noise prevention section of the Society of German Engineers.

LIMITATIONS of SCIENCE. By J. W. N. Sullivan. N. Y., Viking Press, 1933. 307 p., 9x6 in., cloth, $2.75. Only one chapter of this interesting work is concerned with the "limitations" of science. The remainder is concerned with its achievements and future objectives. Affords a picture of the whole field of scientific thought, adapted to the needs of laymen.

SCIENCE MUSEUM, SOUTH KENSINGTON. HANDBOOK of the COLLECTIONS ILLUSTRATING ELECTRICAL ENGINEERING, Part 2. Descriptive Catalogue. London, His Majesty's Stationery Office, 1933. 96 p., illus., 10x6 in., paper, 2s. (Obtainable from British Library of Information, N. Y., $.061.) Contains the substance of the descriptive labels attached to the exhibits in the valuable electric power collections of the Science Museum. Over 300 exhibits are described, with photographs of many of the most interesting ones. The pamphlet supplements the historical handbook.

(The) VALUATION and REGULATION of PUBLIC UTILITIES. By J. H. Gray and J. Levin. N. Y. and Lond., Harper & Bros., Publishers, 1933. 143 p., 8x5 in., paper, $0.75; cloth, $1.00. The reader who wishes to become acquainted with the general features of the problem of utility regulation should find this book a clear, concise outline of the subject. The history of regulation is briefly traced and the attempt at regulation by commissions is analyzed. The reasons why present methods have failed to meet public needs are discussed.

VDI 71. HAUPTVERSAMMLUNG, Friedrichschafen/Konstanz, 1933. VORTRÄGE und AUSSPRACHEN. Berlin, VDI-Verlag, 1933. 157 p., illus., 12x8 in., paper, 3 rm. The papers presented at the 1933 meeting of the Society of German Engineers are presented here in a single volume. These papers are grouped under several headings: food and housing, welding, flow, light construction, civil engineering, steam boilers, textiles, and technology and economics.

BUILDING an ENGINEERING CAREER. By C. C. Williams. N. Y. & Lond., McGraw-Hill Book Co., 1934. 247 p., illus., 8x6 in., cloth, $2.00. Based upon the orientation and motivation courses given at the State University of Iowa. Aims to give the student a preview of the character of the profession and of its relation to social organization, to assist him to adopt efficient methods of study, to indicate the nature of the engineer's mode of thinking, to afford a historical background, and to indicate future possibilities.

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MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

Electrical Features of Ford Exhibit at Chicago Fair.—One hundred miles of electric wiring, more than 225 electric motors, a lighting display which includes a battery of 9,000 concealed floodlights, an amplifying system containing more than 750 loudspeakers—this is only part of the electrical installation for the Ford Exposition Building at the 1934 World's Fair in Chicago. The huge Ford project, covering over 11 acres, will require a load of 6,000 kilowatts, or more than a third of the total electric capacity of the entire Fair in 1933. The exhibits will show in actual operation practically all of the steps required in Ford manufacturing, from the raw materials to the finished parts of cars.

Inventions Service for Manufacturers.—A new service for the manufacturer, to keep him advised month by month of the progress and availability of new inventions in his field, has been announced by Inventions Digest, Inc., 310 South Michigan Ave., Chicago. This service collects descriptions of recent inventions from patent attorneys and reports news of these inventions to manufacturers. Subsequent negotiations for sale or licensing are handled direct between the manufacturer and the inventor's attorney.

New Power Connectors.—A complete line of outdoor, full-bolted electric power connectors has been announced by the General Electric Co., enabling power connections to be made between electric conductors, or between conductors and terminal parts with minimum time and expense. The outstanding feature of these connectors is the line pressure contact obtained by means of a series of thread like cuts on the serrated surface. These pressure contact lines also serve to bite into the conductor and assure a tighter joint. The connectors, of high conductivity copper alloy, have the same current carrying ratings as extra-heavy, iron-pipe-size copper tubing of 98% conductivity.

Trade Literature

Motor Generator Sets.—Bulletin 1155, 24 pp. A comprehensive treatment of this type of equipment; illustrated. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Surge Proof Transformers.—Bulletin D.M.F. 8323, 8 pp. Describes new, surge proof, distribution transformers. Westinghouse Electric & Mfg. Co., East Pittsburgh.

Distribution Cutouts.—Bulletin GEA-1673, 52 pp. Describes enclosed, open, and oil type cutouts and fuse links. General Electric Co., Schenectady, N. Y.

Motors.—Bulletin 167, Part 8, 4 pp. Describes type RD direct-current, compound-wound motors. Wagner Electric Corp., 6400 Plymouth Ave., St. Louis, Mo.

Weatherproof Wires and Cables.—Bulletin 8 pp. Describes URC weatherproof wires and cables. General Cable Corp., 420 Lexington Ave., New York.

Diesel Electric Locomotives.—Catalog 1994, 80 pp. Describes Westinghouse Diesel engines and 15 standard sizes of Diesel electric locomotives. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Mining Cable.—Bulletin GEA-1920, 12 pp. Describes tellurium-compound mining cable for various mine services, including machinery, gathering-reel locomotives, power distribution, telephone circuits, etc. General Electric Co., Schenectady, N. Y.

Network Cable.—Bulletin, 4 pp. Describes a non-metallic sheathed, rubber insulated, braided network cable, extremely resistant to the penetration of oil, moisture, acids, etc. General Cable Corp., 420 Lexington Ave., New York.

Expulsion Protective Gaps.—Bulletin GEA-1858A, 12 pp. Describes expulsion protective gaps for the protection of transmission-line insulation against lightning flashovers and resultant line outages. General Electric Co., Schenectady, N. Y.

Control Equipment.—Catalog, 40 pp. Describes practically all control products manufactured in both the Switch and Panel Division in Detroit and Industrial Controller Division in Milwaukee. Includes prices. Square D Co., Detroit, Mich.

Luminous Fountains.—Bulletin C-1982, 16 pp. Describes 3 standard types of illuminated fountains for estate gardens, public parks, etc. A number of fountain installations are illustrated in color. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Alsimag and Lava Insulators.—Bulletin 34, 28 pp. Describes composition ceramic materials of high dielectric and mechanical strength, widely applicable in the electrical industry and available at moderate costs. American Lava Corp., Chattanooga, Tenn.

Electric Heating Units.—Bulletin GEA-1520B, 52 pp. Describes immersion heaters, cartridge units, strip heaters, calrod units, gluepots, air heaters, soldering irons, control equipment, etc. General Electric Co., Schenectady, N. Y.

Wood Conduit.—Booklet, entitled "The Trend toward Wood Conduit," relates the history of this equipment from 1619 and emphasizes a conduit that has been developed and is capable of carrying lines with 33,000 volts. Installations are illustrated. Southern Wood Preserving Co., Dollar's Savings and Trust Bldg., Pittsburgh, Pa.

Network Protectors.—Catalog 35–500, 12 pp. Describes type CM-2 heavy duty network protectors. The latest refinements in all types of this equipment for heavy duty service, including submersible and open-type units, transformer-mounting units and a compact unit for temporary use on new construction, are illustrated. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Truck and Trailer State Regulations.—Handbook, 56 pp. Outlines the regulations and laws of each state, giving the size and weight restrictions of trucks and trailers. The interpretations of the laws are arranged in tabular form and are approved by a responsible public official of each state, whose signature appears below the interpretation. The Four Wheel Drive Auto Co., Clintonville, Wis.

Instrument and Control Switches. Catalog 9, 8 pp. Describes a new line of instrument and control switches, designated type "R Rotary." The instrument switches are used in connection with electrical measuring instruments and the control switches are employed for establishing proper connections to air and oil circuit breakers and similar equipment. The new line has been worked out to provide a switch for practically every known requirement. Roller-Smith Co., 233 Broadway, New York.

Megger Instruments.—Bulletin 1375. Describes the Megger capacity meter, a portable, direct-reading, multi-range, microfarad or capacity meter, which includes for the first time in an instrument of this character a self-contained source of test current.—Midget Megger Circuit Testing Ohmmeters.—Bulletin 1380. Describes midget Megger circuit testing ohmmeters for quick measurements of resistance from as low as a fraction of an ohm to as high as 200,000 ohms. James G. Biddle Co., 1211 Arch St., Philadelphia, Pa.

Field Intensity Meter.—Bulletin 40, 8 pp. Describes a new radio field intensity meter, Type TMV-75-B. The instrument, complete in two carrying cases, consists essentially of an extremely sensitive loop receiver of the superheterodyne type, incorporating a self-calibrating oscillator. The frequency range is from 25 kc to 20,000 kc. The field intensity range is from 20 micro-volts per meter to 6 volts per meter; readings are direct. The instrument is of value in radio transmission surveys and interference location. RCA Victor Co., Inc., Camden, N. J.

Capacitors.—Bulletin GEA-77F, 28 pp. Describes Pyranol-treated capacitors for power-factor improvement. These are applicable over a wide range of service conditions and are of 4 general types: box-type, small rack-type, small outdoor, and large rack-type capacitors for either indoor or outdoor installations. These capacitors are treated and filled with Pyranol. This new liquid is an outstanding dielectric material for capacitors because its extraordinary insulating and dielectric properties permit an unusually small capacitor for a given rating; also because it is nonflammable. General Electric Co., Schenectady, N. Y.

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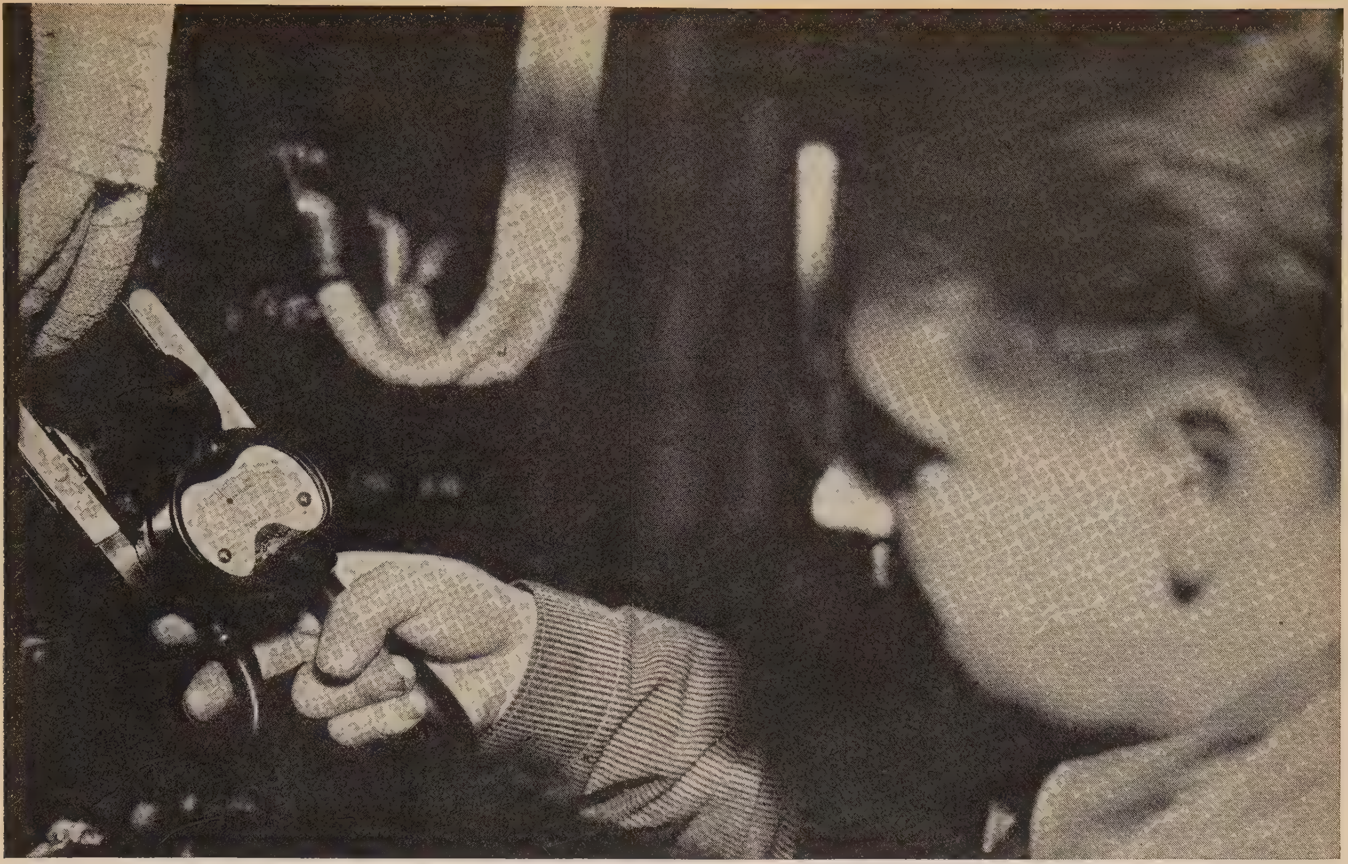

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Employment Bulletin

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MAINTAINED by the national societies of civil, mining, mechanical, and electrical engineers, in cooperation with other organizations. An inquiry to any of the three offices will bring full information concerning the services of this bureau.

A weekly bulletin of engineering positions open is available to members of the cooperating societies at a subscription of $3 per quarter or $10 per annum, payable in advance.

Replies to the following announcements should be addressed to the key numbers indicated and mailed to the New York office.

●

Men Available

E.E. DES, 32, married; 4 1/2 yrs steam pwr plants, substations and high tension lines 5–100 kv; 4 yrs indus engg, control eqpt and generator stations; also 2 1/2 yrs shop exper. D-3000.

GRAD ENGR, 29, single, desires pos as distr engr; 7 yrs varied util exper: des, constr of distr, transm lines, rehabilitation of substations, standardization of distr constr, estimates, cost records. D-1977.

E.E., Univ grad; 4 yrs draftg, des, constr, engg modern hydro, steam pwr plants, substations, ry electrification; 5 1/2 yrs leading mfg concern engg of automatic, manual switchgear eqpt. Foreign languages. B-7938.

GRAD ENGR; 2 yrs post grad work in physics; 12 yrs exper elec insulating problems, materials and processes. Exec and organizing ability. Is seeking a pos of responsibility. B-9406.

PHYSICIST, Ph.D., 43; 6 yrs radio devpmt engr with Westinghouse and Victor RCA; 4 yrs in indus research in electricity, optical instruments and refrigeration; 4 yrs instructor in leading univ. C-2588.

A.B., with training in E.E. Exper in teaching illumination des, gen elec engg, long tel cable planning, cost studies and particularly in engg correspondence. D-2342.

INSTRUCTOR, E.E., M.Sc., one yr additional grad study; elec com; 29, single; 5 yrs teaching exper in engg. Desires teaching or research pos in the East. D-2912.

E.E., B.S., 1924 Univ So. Calif. M.S. 1933 Univ Mich. Married, 31. One yr testg Gen Elec; 4 yrs engg practice pub util; 4 yrs instructor E.E. state univ Desires teaching. C-1209.

E.E., M.S., Stevens 1934, B.S. at N.C.E. 1933. Honorary scholastic engg soc. Age 23, single. Exper: Office work, draftg. Conscientious worker. Desires engg pos. East preferred. D-2966.

JUNIOR E.E., B.S., Oregon State Col, 1932, married, 24. Street ltg instal, wiring exper. Com field, radio preferred, but desires any pos any elec field, helper. West preferred. Salary secondary. D-3005.

RECENT GRAD, M.S. in E.E., B.E.E. cum laude, seeks any pos offering exper. Salary and location secondary. Can supply any necessary ref. D-3011.

COMMERCIAL ENGG, B.S., E.E., B.S., Washington, June 1934, 25, married. Tau Beta Pi. Typing, shorthand. One yr business training. Pos leading to sales engg, factory mgmt. Exper more important than salary. D-3017-345-C-3-San Francisco.

GRAD E.E., 33, married; 4 3/4 yrs in E.E. office of large eastern RR; 5 yrs as electrician on Diesel and turbo-elec ships. Desires pos. affording engg exper and advancement. C-8160.

GRAD RENSSELAER POLY INST, E.E., 1932, 22, single. Sigma Xi. Wants job in any elec field. Available now. D-1716.

E.E. GRAD, 33 single. Exper: Instal, maintenance elec apparatus; testg elec meters, relays; oprn, maintenance steam pwr plants, condensing, non-condensing turbine units, gas, oil-fired boilers. Constr, des, estimations, calculations. C-3764.

E.E. (B.S. and Prof), 44, married; 17 yrs des and cost, maintenance and plant extension studies in lt, pwr and tel engg. Available immed. NYC or vicinity. D-2183.

E.E., 48, member Sigma Xi, desires research pos where long exper in the pwr field will be useful. This includes pwr system, indus work, elec surveys. Univ grad, analytically inclined. B-1923.

E.E., 35; 10 yrs des, devpmt, estimating central station, substation, transm, indus bldgs; one yr research cables and dielec tests, one yr elevator tests. N. J. license; German and English languages. C-5473.

E.E., B.S., 1933, Univ of Penna, single, 25. Desires pos as cadet engr any engg branch or work related to engg. Eastern State location preferable. Available immed. Good conscientious worker. D-2753.

E.E. GRAD, 28, married, desires pos des, devpmt, teaching. One yr Westinghouse student course; 6 mos Westinghouse Des School; 1 1/2 yrs des fractional hp motors; 2 1/2 yrs des indus motors. C-5051.

PATENT ATTORNEY, 28, single, E.E., S.B. (M.I.T.), LL.B., M.P.L., member of Bar, 5 yrs examiner in an elec div of U.S. Patent Office. Location immaterial. C-3550.

E.E., B.S., married, 39; 2 yrs Westinghouse, tester; 9 yrs large oil refinery, gen engg and draftg. War veteran. Ref. Available now; salary secondary. B-7940.

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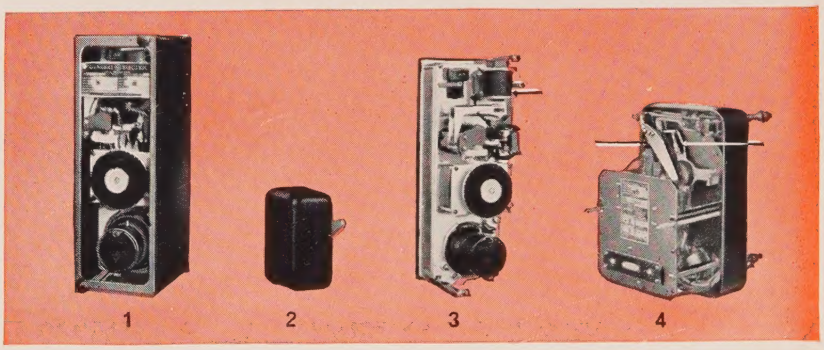

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